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Post-Flashover Fires in Simulated Shipboard Compartments—Phase III Venting of Large Shipboard Fires

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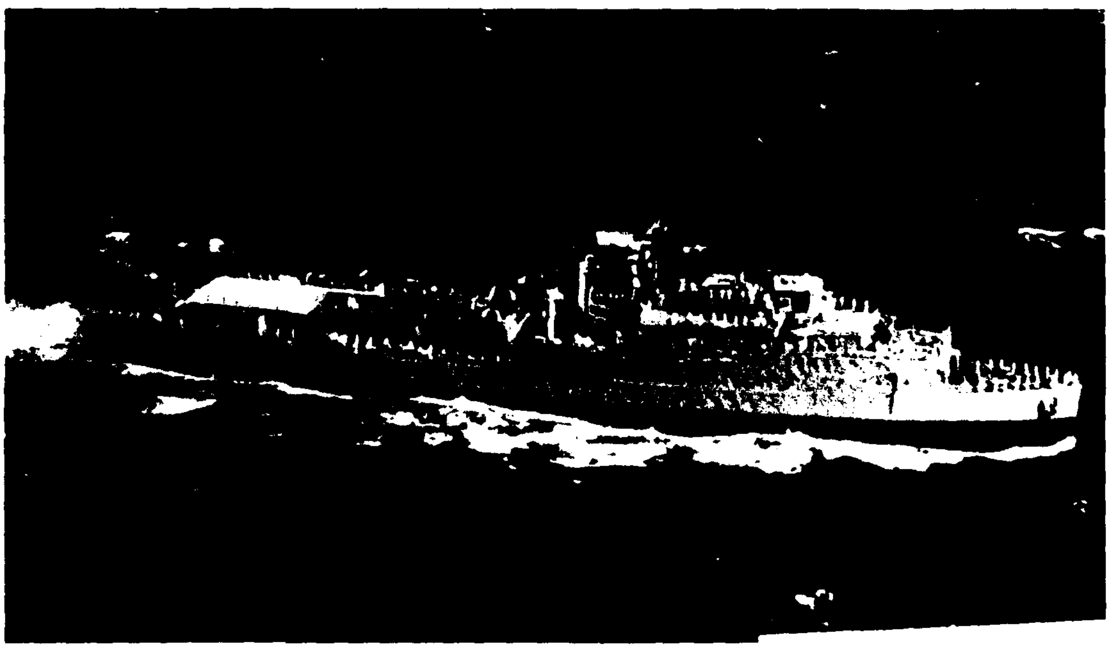

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13. ABSTRACT (*Maximum 200 words*)

As part of the Internal Ship Conflagration Control Project, post-flashover compartment fires were created in small and large scale shipboard compartments. The venting test series described in this report was an extension of earlier work which quantified the heat transfer characteristics from post-flashover fires in steel enclosures. The objective of the tests was to quantify the effects of venting a large fire, particularly natural venting and its effect on thermal insults.

Tests were conducted both in a steel mock-up at NRL CBD and on board the NRL research test ship, ex-USS SHADWELL. Venting of both the fire compartment and adjacent spaces was investigated. As anticipated, large vent areas are required to achieve significant reductions in the thermal insult to spaces adjacent to the fire compartment. Smaller vents may be effective in relieving smoke, which could help firefighters gain access to the fire. Mechanical ventilation, in the form of a portable water motor fan, was demonstrated to be more effective than natural venting for relieving heat in a compartment adjacent to a fire.

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POST-FLASHOVER FIRES IN SIMULATED SHIPBOARD COMPARTMENTS—PHASE III VENTING OF LARGE SHIPBOARD FIRES

1.0 BACKGROUND

The Internal Ship Conflagration Control (ISCC) program was initiated to address issues raised by the missile-induced fire on the USS STARK. The overall objectives of the program were to develop guidance to the Fleet on the control of horizontal and vertical fire spread and to develop concepts and criteria for new ship design to obviate the kind of devastation that occurred on the STARK. The program included intermediate scale fire tests in a simulated shipboard compartment located at the Naval Research Laboratory (NRL) Chesapeake Bay Detachment (CBD) and large scale tests in full scale compartments aboard the NRL fire test ship, the ex-USS SHADWELL, in Mobile, AL.

During the initial stages of the ISCC program, an analysis was conducted at CBD to characterize the conditions occurring during post-flashover compartment fires [1]. During these characterization tests, a "worst case" fire was developed to be used during the fire dynamics test series conducted on board the ex-USS SHADWELL [2]. The fire dynamics test series on the SHADWELL were used to observe the thermal conditions occurring in and around the fire compartment for a large, post-flashover fire [3]. Estimates on fire spread rates were also developed in both test series. Using these evaluations as a baseline, the effect of naturally venting of smoke and hot gases during a major conflagration was evaluated both at CBD and the SHADWELL. This report describes the results of these tests.

Venting is the systematic removal of smoke, gases, and hot air from a structure. These hot gases are then replaced by a supply of cooler air which can facilitate firefighting procedures. The importance of ventilation cannot be overlooked. It increases visibility for quicker location of the seat of the fire. It decreases the danger to trapped occupants by channeling away hot, toxic gases. At the same time, it has the potential to accelerate fire growth if performed improperly.

Chapter 555, Section V, of the *Naval Ships Technical Manual* (NSTM) on firefighting [4] suggests that venting should be considered when the area above the fire compartment is either top side or in a large area open to the weather such as a hangar or well deck. NSTM also states that the minimum vent area should be one square foot and that the larger the hole, the quicker the heat and smoke will be vented from below.

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The one square foot minimum vent area was a qualitative recommendation based on judgment and experience and not on a particular set of conditions and/or data. The objective of this analysis was to quantify the effect of vent size by evaluating the relation between vent area and the consequent reduction in the thermal conditions in and around the fire compartment. Chapter 9 of NWP 62-1, *Surface Ship Survivability*, also provides general venting doctrine.

2.0 OBJECTIVES

The objective of this evaluation was to determine the impact of venting smoke and hot gases during a major conflagration. The primary emphasis was on naturally venting to reduce the thermal impact to personnel and equipment. The analysis focused on the relation between vent size and the consequent reduction in the thermal insult to the ship. Venting of both the fire compartment and adjacent spaces was investigated.

3.0 APPROACH

The approach taken to analyze the effects of venting incorporated information determined during the earlier stages of the ISCC program. During this test series, the effects of venting on both the fire compartment and areas adjacent to the fire compartment were evaluated. Initially, the problem was bounded using the intermediate scale mock-up constructed at CBD to characterize post-flashover fires in simulated shipboard compartments [1]. The problem was then further refined on the ex-USS SHADWELL under normal full scale shipboard conditions.

The small-scale studies at NRL CBD identified the effects of ventilation on post-flashover fires. These studies investigated the effects of vent size above and below stoichiometric burning, i.e. for ventilation and fuel controlled fires. Since the investigations focussed on post-flashover conditions (full compartment involvement), vent size per se does not dramatically impact on the fire compartment temperature. A temperature range of 650-1050°C was observed for fire compartment ventilation factors of 6.2 - 20.1 $m^{-1/2}$, at hydrocarbon fuel flow rates equivalent to 1.6 - 11.2 MW. For post-flashover situations, opening sizes would have dramatic effects only if they are very small or large.

There was no combustible loading in adjacent spaces in the CBD and the ex-USS SHADWELL tests. Since ventilation of a post-flashover fire compartment is essentially a moot point in terms of temperature and smoke in the originating compartment, the investigation focussed on the thermal conditions in areas adjacent to the fire compartment.

4.0 CBD TESTS

4.1 Approach

The amount of smoke produced and contained in an enclosure during a compartment fire makes accessing a fire by the repair party difficult. High in the compartment, gases are hot and potentially toxic. At lower elevations in compartments and passageways, there is relatively cool and uncontaminated air. As the hot gasses begin to accumulate, the smoke layer begins to drop closer to the deck. The escaping hot gases may be responsible for fire spread from the compartment of origin to spaces around the fire compartment.

One method to prevent an enclosure from filling with smoke is by opening a vent in the overhead to exhaust the hot gases and smoke produced by the fire. The removal of smoke should cause a decrease in the depth of the smoke layer, i.e. the clear area below the smoke is increased. Any increase in height of the smoke layer may substantially aid in firefighting access. The increase in the height of the smoke layer is mostly attributed to the increased flow of air into the compartment. This increased flow of cooler, uncontaminated air serves to increase visibility and cool the areas leading into the fire compartment. For post-flashover situations, the increase of ventilation is not a particular concern in terms of fire size since, by definition, all combustible material is already involved.

Most of the previous discussion assumes that the fire is fuel lean. Alternatively, if the fire is fuel rich (a fire containing an excess amount of fuel), the results of increased ventilation may be different. A fuel rich fire is characterized by flames protruding out the doors and hatches leading into the compartment. Insufficient oxygen is available to consume all of the pyrolized fuel, therefore, the combustion process is completed outside the compartment where oxygen is more readily available. Venting a fuel rich fire may cause the temperature in the fire compartment to increase due to the increased availability of oxygen. The magnitude of flame protruding from the vent opening may also be substantially greater in the case of a fuel rich fire.

The CBD tests were conducted to evaluate the effect and feasibility of venting the fire compartment in an attempt to reduce the overall threat to adjacent spaces. The fire compartment was vented using various sized openings. Two fire sizes were used in this evaluation. The first fire represented a fully-involved compartment, approaching flashover conditions. The second fire was a fuel-rich fire and was selected as a "worst case" fire to analyze the effects of adding air to an oxygen-starved fire. Presumably, venting such a fire may increase the burning (energy release) rate, causing the thermal threat to increase.

4.2 Setup

The mock-up constructed at CBD for the post-flashover characterization test series [1] was used in this evaluation. The mock-up consisted of four 2.4 x 2.4 x 2.4 m (8 x 8

x 8 ft) cubical enclosures, three cubes long and two cubes high in the center as shown in Figs. 1 and 2. The mock-up was constructed of 0.95 cm (3/8 in.) thick steel plates. Stiffeners having "T" shape cross-sections were welded vertically to the center of each wall in all compartments. The outside lower compartments each contained two 66 x 167.6 cm (26 x 66 in.) openings, one to the outside air and one to the center compartment. The upper compartment contained one door opening to the outside air and one (0.61 m (2 ft) diameter) hatch opening in the overhead. The center compartment contained four doors, one to each of the adjacent compartments and two to the outside air.

The compartment located at the east end of the mock-up was used as the fire compartment for these tests (Fig. 2). A 1.2 x 2.4 m (4 x 8 ft) adjustable vent was installed in the overhead of the compartment. All doors opening to the weather except the one in the compartment at the opposite end (west compartment) were closed for these tests. All other doors remained opened. With the doors arranged in this fashion, it was necessary that air for combustion be drawn through all three lower compartments, i.e. from the west compartment, through the center compartment, and finally into the east (fire) compartment. Hot gases and smoke were also drawn through the overhead of the three lower compartments. This configuration simulated a corridor leading to a fire compartment.

The fueling and nozzle assemblies are shown in Figs. 3 and 4. This system was used to achieve post-flashover fire conditions in the fire compartment as quickly as possible. The fueling control station was located 6.1 m (20 ft) behind the fire compartment. Quick operating quarter-turn valves were installed for manual shutdown of the system. A nitrogen system was used to pressurize the fuel storage tank and to flush out the fuel system after each test. The fueling station was manned at all times during testing.

4.3 Instrumentation

The instrumentation scheme developed for the original characterization of post-flashover fires was modified for this evaluation. The instrumentation layout is shown in Fig. 5. Exact dimensions of instrumentation placement are contained in Reference [1].

Thermocouple trees were installed in all compartments to provide air temperature measurements. All thermocouples used in the test series were Type K (chromel-alumel). Inconel-sheathed thermocouples were installed in the fire compartment while high temperature glass-braided thermocouples were installed in the adjacent compartments. Matrices of inconel-sheathed thermocouples were installed on both exposed and unexposed surfaces of the bulkheads and decks bounding the fire compartment to provide information on the energy conducted through the steel plates. These thermocouples were fastened to the boundaries by drilling a small hole and peening the end of the thermocouple to the surface.

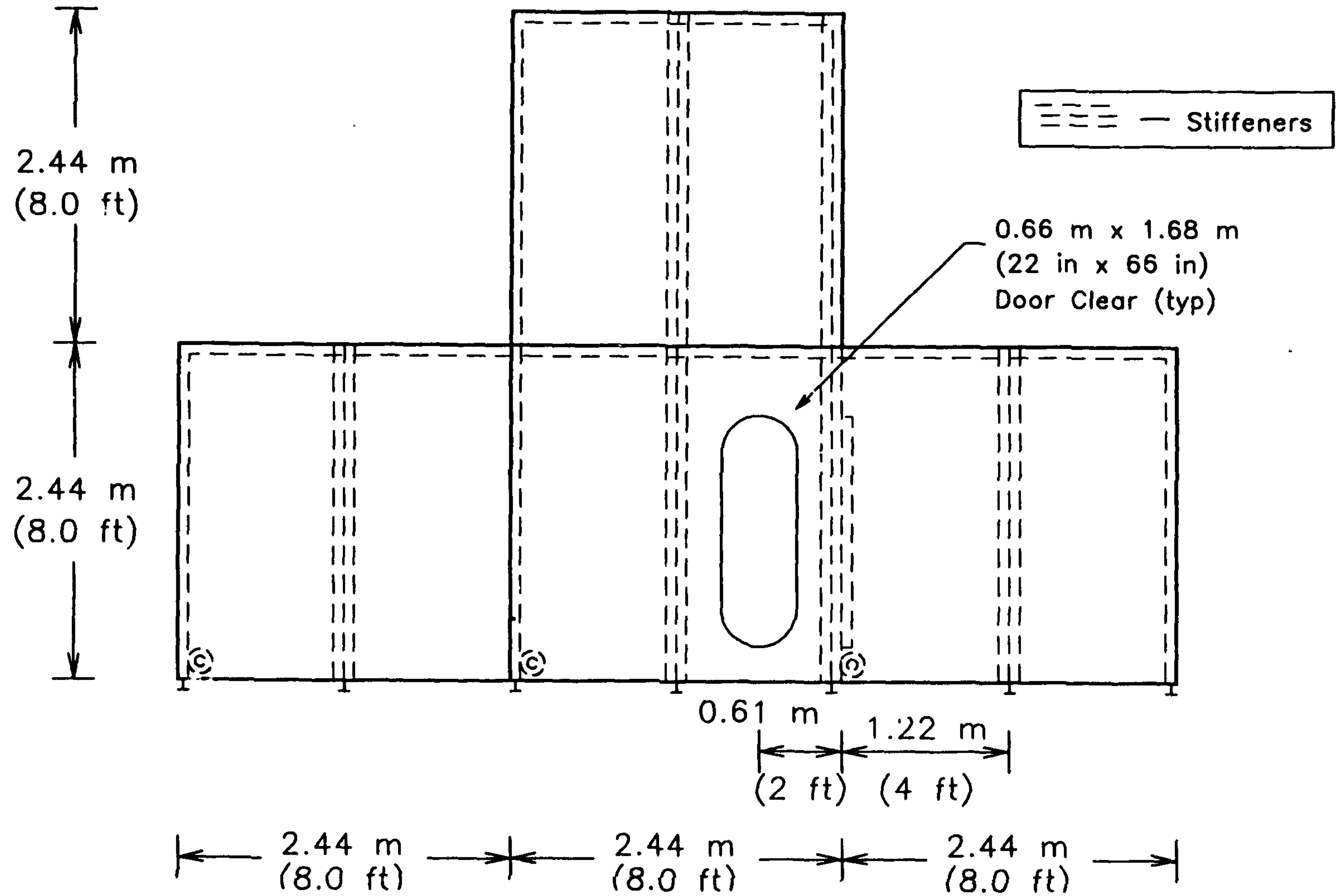
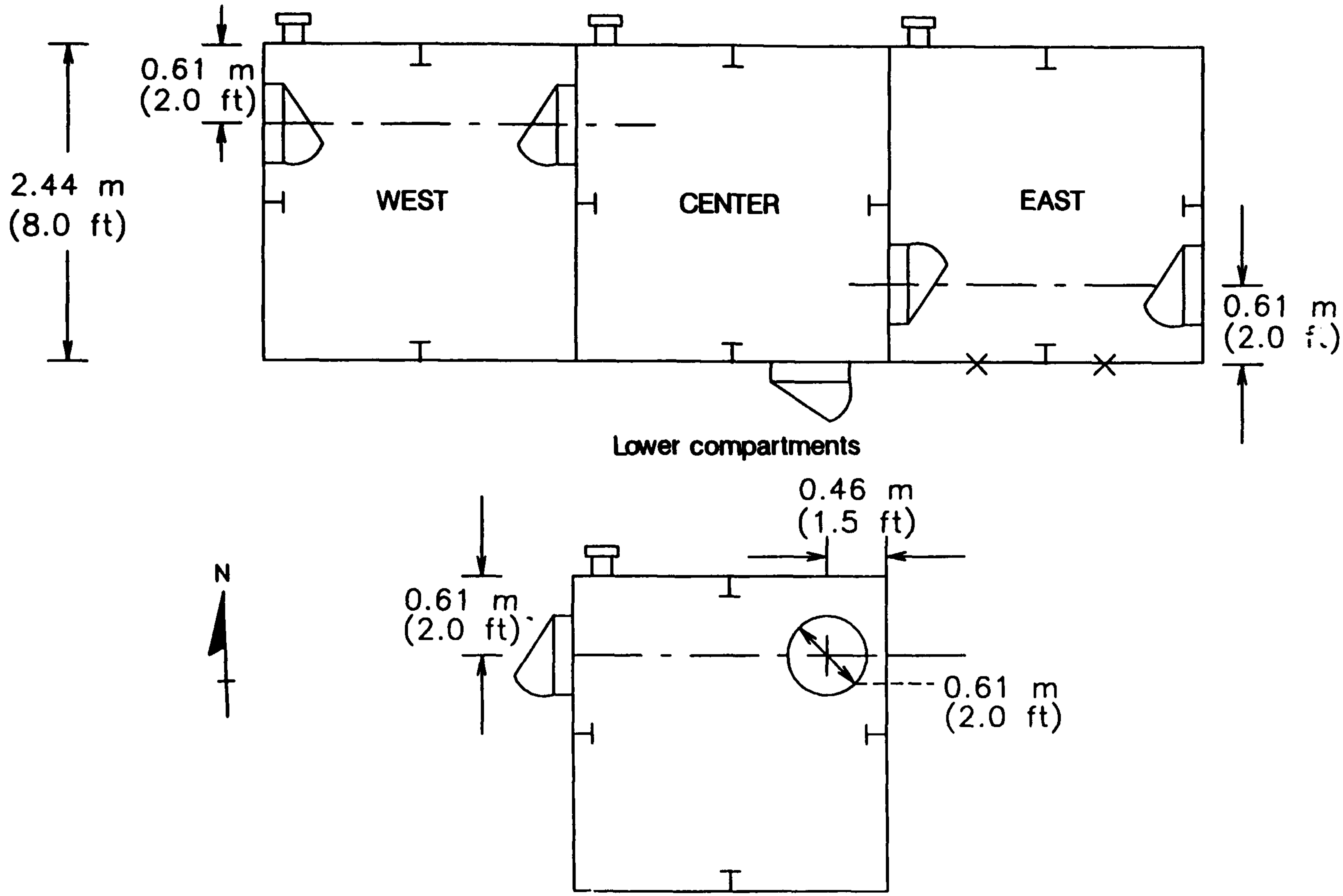


Fig. 1 - CBD compartment mock-up (elevation view)



Lower compartments

Upper compartment

Fig. 2 - CBD compartment mock-up (plan view)

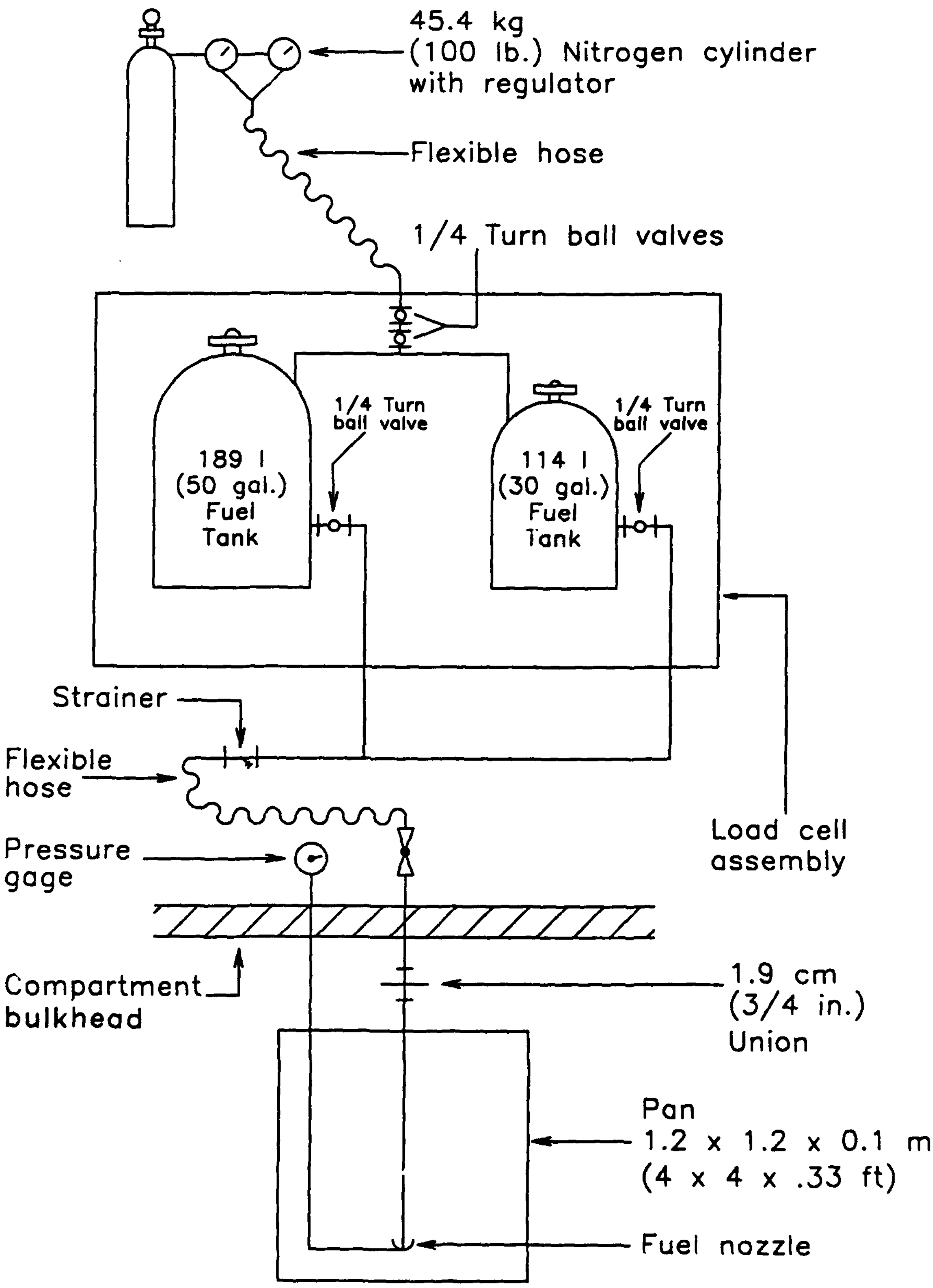
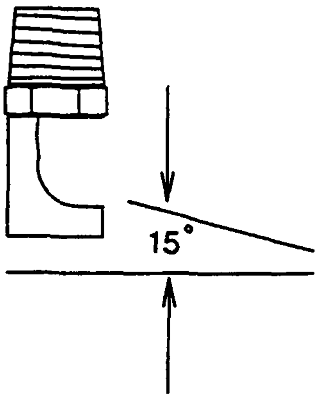
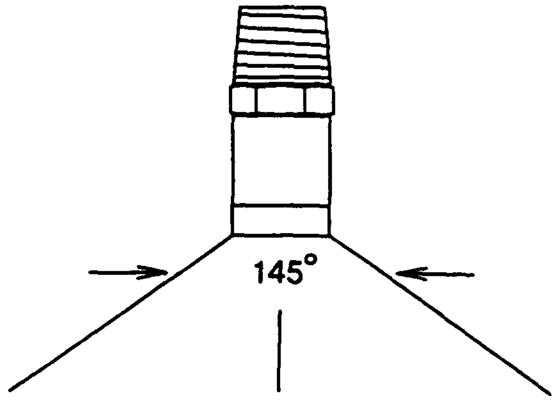


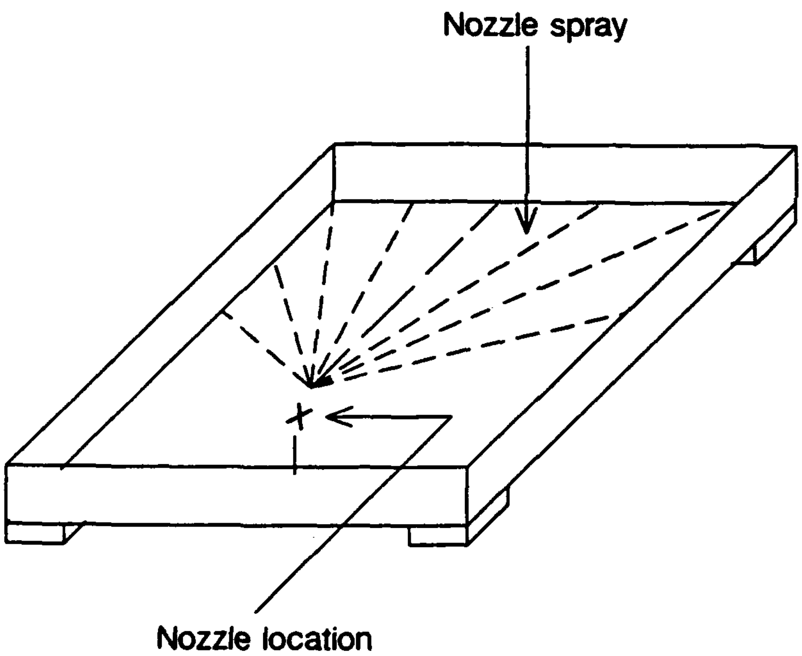
Fig. 3 - CBD fueling system



Bete FF 125 145 nozzle
Side elevation



Bete FF 125 145 nozzle
Front elevation



Fuel pan - schematic

Fig. 4 - Nozzle assembly for CBD tests

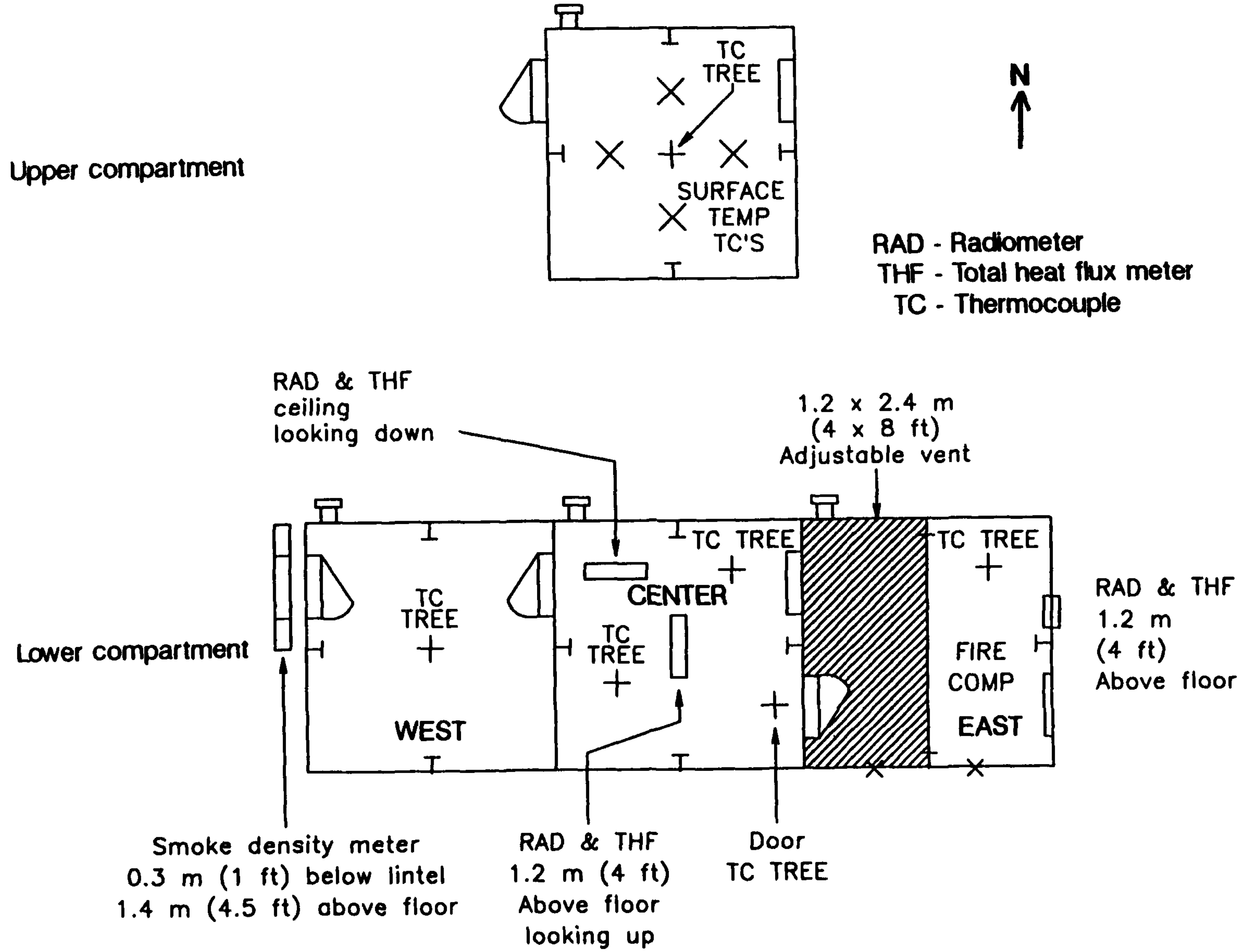


Fig. 5 - Instrumentation layout for CBD tests

Gardon-type wide angle calorimeters and radiometers were installed, generally in pairs, to measure total and radiative heat flux, respectively. Radiation and total heat flux data collected from each compartment served as indicators of the energy being removed from the compartment during the venting process. High range (330 kW/m^2 (30 BTU/ft^2 s)) transducers were installed in the overhead of the fire compartment and medium range (110 kW/m^2 (10 BTU/ft^2 s)) transducers were installed in each of the adjacent compartments. A radiometer and calorimeter were installed 1.2 m (4 ft) above the deck in the center compartment to measure the radiant and total heat flux at waist level in the space leading to the fire compartment. This measurement was used to analyze the tenability of the space leading to the fire compartment. Waist level was selected assuming that a fire party would approach the fire compartment in a crouching or crawling position.

Smoke optical density was measured across the doorway of the west compartment 1.4 m (4.5 ft) above the deck. A sealed beam smoke meter having a 1 m path length was mounted flush with the door opening. The output signal was converted directly to optical density per meter. Load cell assemblies installed under the fuel storage tank provided mass loss rates from which fuel flow rates were calculated.

An IBM-compatible computer and seven EXP-16 cards produced by Metrabyte Corporation were used to scan the instruments in ten second intervals. A commercial software package, Lab Tech Notebook, was used to drive the data acquisition system.

4.4 Procedures

Upon completion of the pre-test checks of instrumentation, fueling system, and safety equipment, the area was cleared for the start of the test. Once all test personnel were in position, the data acquisition system, video cameras, and stopwatches were all started marking the beginning of the test. These systems were activated one minute before ignition to collect background data and to record the ignition information. Thirty seconds after activation of the data systems, a small torch was lit and placed in the fuel pan in the fire compartment. At one minute into the test, the fuel system was charged and the fuel flow rate was adjusted to the desired amount. Eleven minutes into the test (10 minutes after ignition), the vent was opened to the desired size. The test was terminated sixteen minutes into the test.

Two fire sizes were evaluated. The first used 1.9 ℓpm (0.5 gpm) of JP-5 fuel sprayed in the fire pan. The estimated heat release rate, assuming complete combustion, was 1.1 MW (see Reference [1] for heat release estimates). The other fire was 3.8 ℓpm (1.0 gpm) of fuel with an estimated complete heat release rate of 2.2 MW. The 3.8 ℓpm (1.0 gpm) fuel flow rate approximated, in theory, stoichiometric burning. In actuality, the air flow restriction caused by the passageway created by the center and west compartments reduced the effective air flow to the fire. The 3.8 ℓpm (1.0 gpm) fire was observed to burn fuel rich.

For each test, the overhead vent in the fire compartment was varied. The vent sizes investigated were 0, 0.4, 0.8, 1.2, 1.6, and 3.2 m^2 (0, 4, 8, 12, 16, and 32 ft^2). The vent size was varied by sliding a 1.2 x 2.4 m (4 x 8 ft) section cut from the overhead to create the desired opening. For example, to create the 0.8 m^2 (8 ft^2) opening, the overhead section was slid 0.3 m (1 ft) to create a 0.3 x 2.4 m (1 x 8 ft) opening.

4.5 Results

The results from these tests are summarized in Table 1. The reduction in the overall thermal insult is illustrated in Figs. 6 and 7 for the 1.1 MW fires and Figs. 8 and 9 for the 2.2 MW fires.

For the 1.1 MW fires, the temperatures measured in the fire compartment decreased dramatically from 700°C to 300°C (1292°F to 572°F) with increased vent size as shown by the top line in Fig. 6. The effect on the temperatures in the passageway were less pronounced, reducing from 250°C to 150°C (482°F to 362°F). Both the optical density and total heat flux measurements were also observed to decrease dramatically with increased vent size. The optical density was observed to drop from 3 to 0 (optical density per meter) while the total heat flux dropped from 7 to 2 kW/m^2. These reductions occurred within the parameters of no vent to a vent area of ~1 m^2 (10 ft^2).

For the larger (fuel rich) fires, the effects of venting followed roughly the same trends except for the temperatures measured in the fire compartment. The temperatures in the fire compartment were observed to initially increase from 600°C to over 800°C (1112°F to over 1472°F) for a compartment unventilated at the overhead to one containing a vent with an area of ~1 m^2 (10 ft^2). This increase in temperature was attributed to an increase in oxygen in the fire compartment and a resulting higher energy release rate. As the vent area was increased above 1 m^2 (10 ft^2) the temperatures in the fire compartment decreased. The temperatures in the passageway were observed to drop from 450°C to under 200°C (842°F to under 392°F) over the range of overhead vent conditions. The smoke density and total heat flux measurements recorded in the passageway were also observed to have decreased with increased vent size. The total heat flux dropped substantially, from 18 kW/m^2 to 6 kW/m^2 (1.6 to 0.6 BTU/ft^2 s) as the vent size approached ~1 m^2 (10 ft^2).

In summary, venting the fire compartment significantly reduced the thermal insult to the areas around the fire compartment. This reduction in the thermal conditions could potentially slow fire spread and permit easier access to the compartment by firefighting parties. For a fuel-rich fire, venting the fire compartment may increase the temperature in the fire compartment, but a substantial reduction in the threat to adjacent spaces was still observed. The area of the vent opening required to have a significant impact on the thermal conditions varied between the two situations. All vent sizes evaluated in this analysis had some positive effect on the overall conditions. NSTM suggests that a minimum of one square foot is required to effectively vent smoke and hot gases from the fire compartment. These tests show that during a major post-flashover compartment fire,

Table 1. CBD Tests—Summary Data

JP-5 Flow Rate lpm	1.9	1.9	1.9	1.9	1.9	1.9	3.8	3.8	3.8	3.8	3.8	3.8
gpm	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0
Equivalent Energy Release Rate of Fuel MW	1.1	1.1	1.1	1.1	1.1	1.1	2.2	2.2	2.2	2.2	2.2	2.2
Vent Size m^2	0	0.4	0.8	1.2	1.6	3.2	0	0.4	0.8	1.2	1.6	3.2
ft^2	0	4	8	12	16	32	0	4	8	12	16	32
Avg. Fire Comp. Temp. °C	700	600	450	400	300	275	600	650	800	700	700	600
°F	1292	1112	842	752	572	527	1112	1202	1472	1292	1292	1112
Avg. Passageway Temp. °C	250	200	200	175	125	125	450	375	300	225	200	150
°F	482	392	392	347	257	257	842	707	572	437	392	302
Neutral Plane Height m	0.91	1.2	1.5	1.8	2.4	2.4	.61	.91	.91	1.2	1.2	1.8
ft	3	4	5	6	8	8	2	3	3	4	4	6
Total Flux at Waist Height In Fire Comp. kW/m^2	30	15	10	10	10	10	35	40	50	25	20	17
BTU/ft^2-s	2.6	1.3	.9	.9	.9	.9	3.1	3.5	4.4	2.2	1.8	1.5
Total Flux at Waist Height in Passageway kW/m^2	7	4	3	2	1	0	18	15	7	5	4	2
BTU/ft^2-s	.6	.4	.3	.2	.1	0	1.6	1.3	.6	.4	.4	.2
Optical Density Per Meter	3	1	0	0	0	0	4	4	3	3	3	1

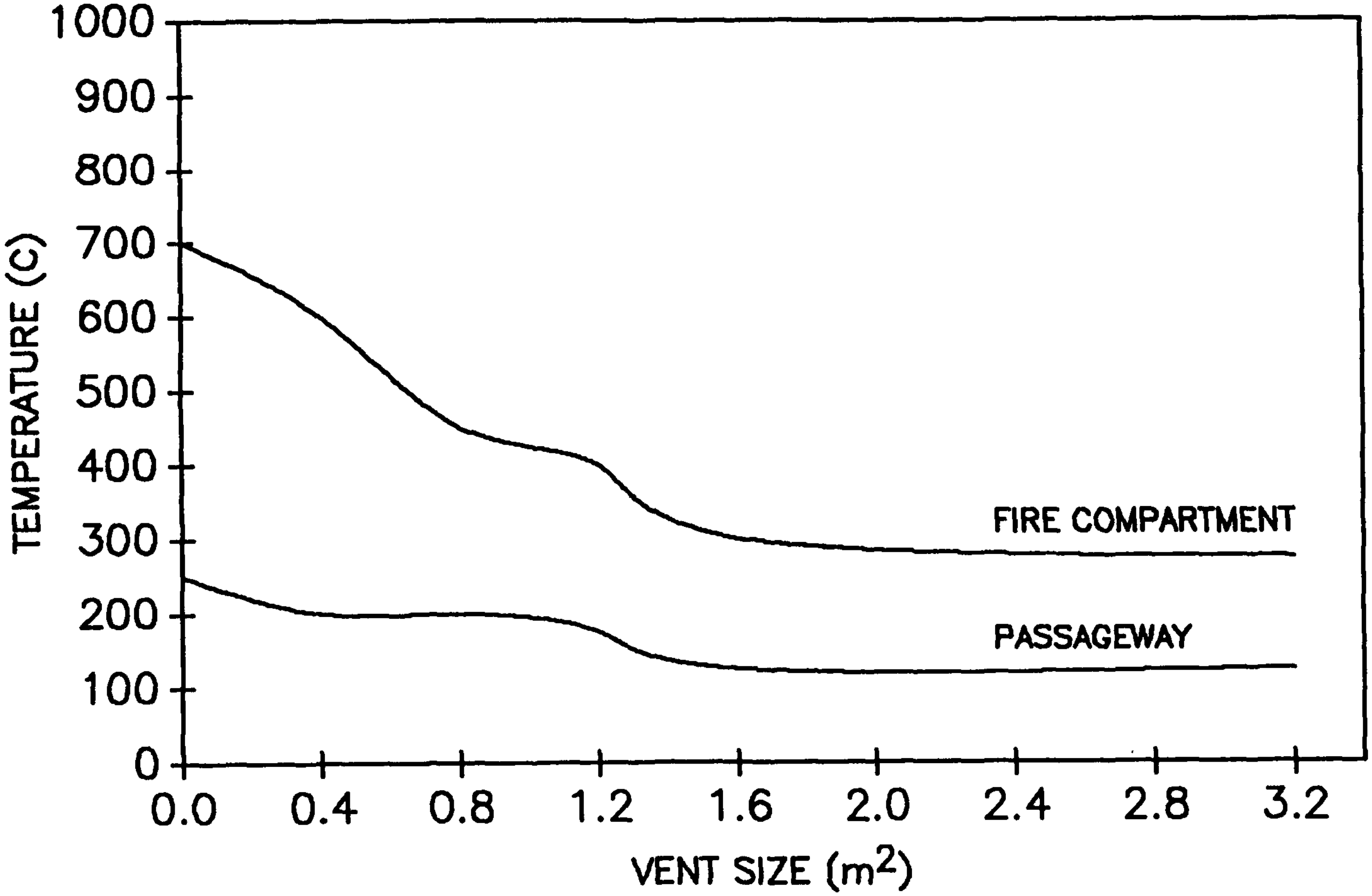


Fig. 6 - Compartment temperatures as a function of fire compartment vent opening size (1.1 MW fire)

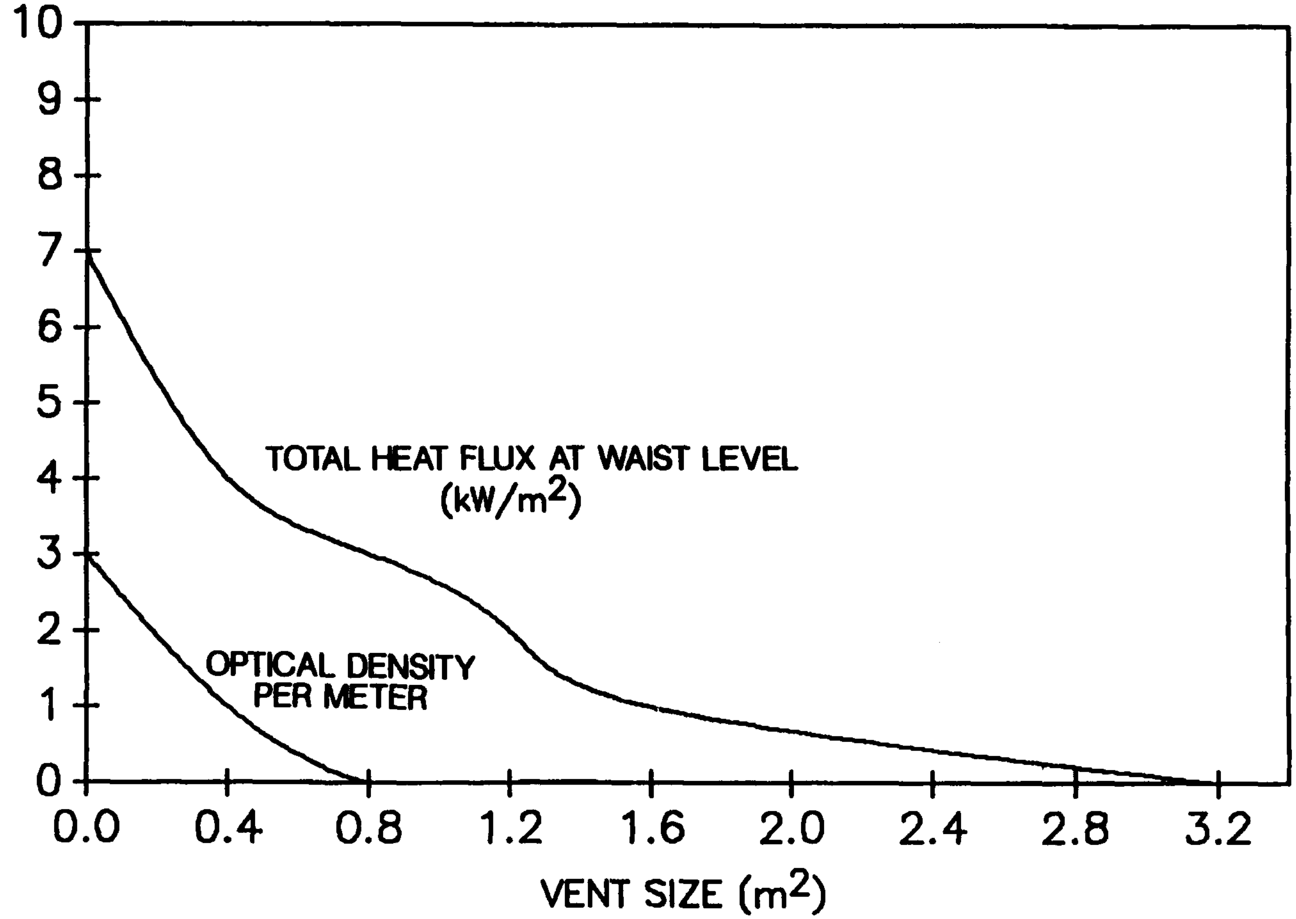


Fig. 7 - Total heat flux and optical density as a function of fire compartment vent opening size (1.1 MW fire)

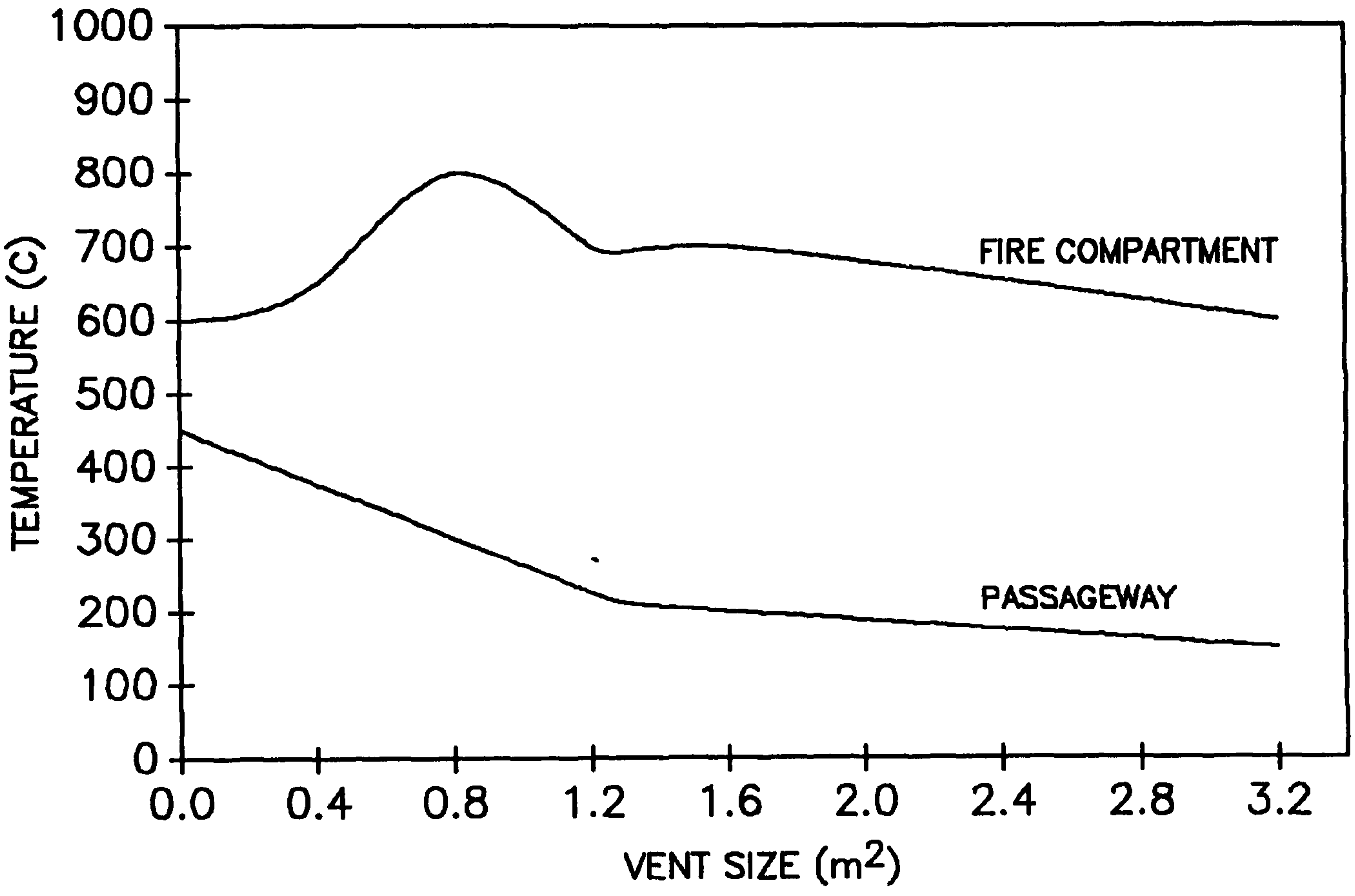


Fig. 8 - Compartment temperatures as a function of fire compartment vent opening size (2.2 MW fire)

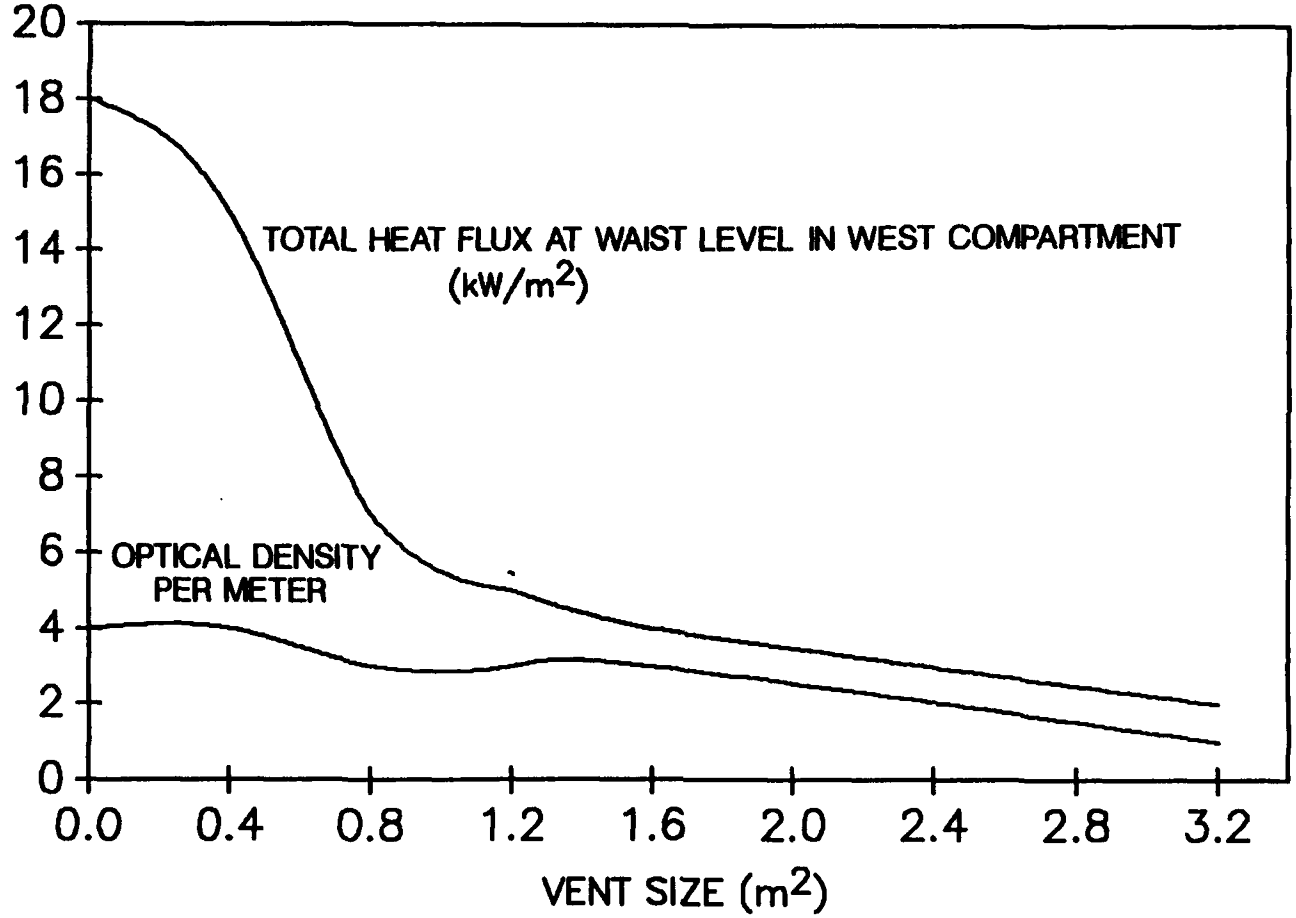


Fig. 9 - Total heat flux and optical density as a function of fire compartment vent opening size (2.2 MW fire)

a vent size on the order of ~1 m^2 (10 ft^2) for the 2.4 m cube may be required to have a significant impact. Such a large vent (e.g., 16% of the overhead surface area) may, however, be unrealistic in most firefighting scenarios.

This discussion has focused on the potential advantages of venting large fires, e.g., a post-flashover fire. By definition, a large fire requires considerable air to support continued combustion. In some cases, the oxygen supply cannot be interrupted, e.g., an opening to weather from battle-induced damage. Judgement must be used when considering the need to vent. For example, a shipboard fire may be extinguished by oxygen depletion alone by securing all closures and ventilation systems. This is a time-honored tactic for combatting shipboard fires and should not be ignored. Rather, when conditions dictate that smoke and/or heat removal will aide in extinguishing the fire, these options should be considered.

4.6 Modeling

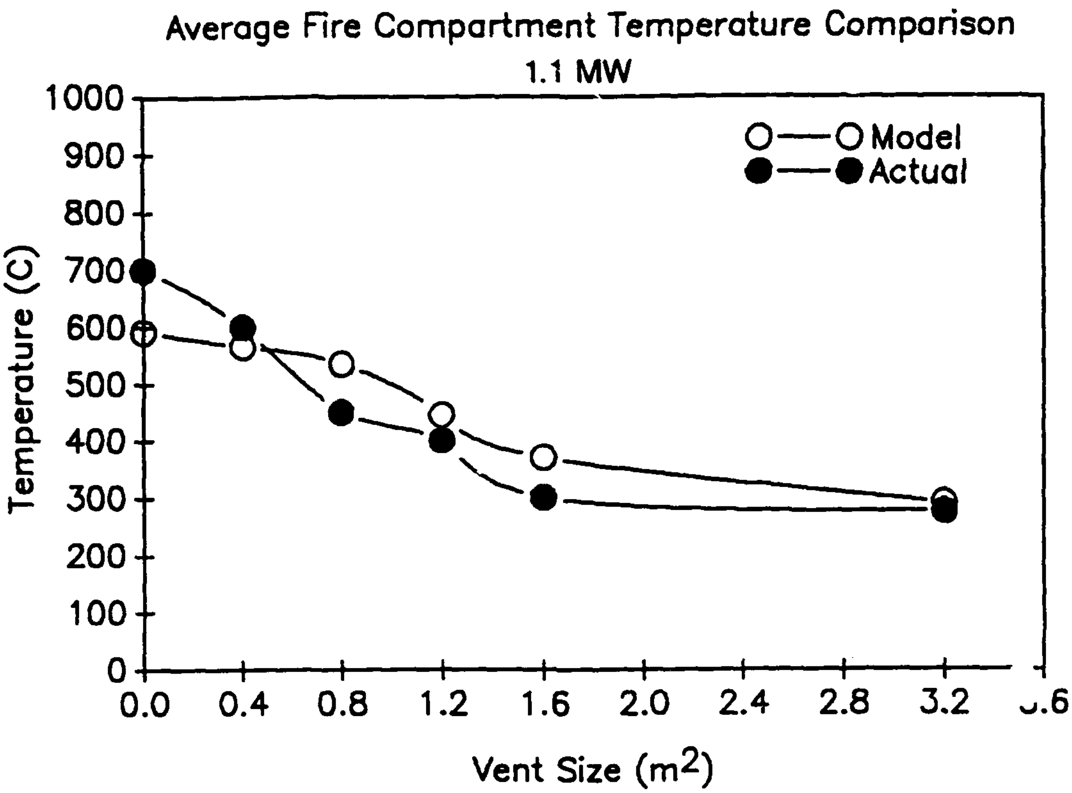
Considerable research has been performed regarding the spread of fire and smoke from a compartment of origin to adjacent spaces. This work was motivated by the need to understand and predict the environments which occur as a fire develops and spreads. As a result of this work, numerical models designed to accurately predict these conditions have been developed. One such model is FAST, which was developed to describe fire growth and smoke transport in multi-compartment structures [5]. This model was selected for this evaluation to serve as a comparison to experimental results. It includes a vertical vent algorithm.

A total of 20 iterations were made using the program. The first ten runs were made to duplicate the conditions in and around the fire compartment for the two unvented tests. Duplicating these conditions provided a baseline to then evaluate the effects of venting. Only a small deviation in the input parameters (compartment geometry) was made to equate the model results to the actual unvented test conditions. For these modeling iterations, the smoke or hot layer reached the floor causing fire to protrude into the adjacent compartment. This, in turn, increased the temperature in the adjacent compartment above the actual results. These conditions occurred even for the smaller fire. To correct this situation, a small vertical vent (0.2 m wide and 1.67 m wide) to the outside air was added to the fire compartment in the model. The need for this correction may be a result of leaks around the adjustable vent in the actual tests. These leaks may have supplied additional air to the fire thus altering the results. After the baseline unvented scenarios were successfully reproduced using this adjustment, the ten tests containing various size vents were modeled as shown in Table 2.

The results of the fire model are in good agreement with the majority of the results (Figs. 10-12). The temperatures in the fire compartment for the 2.2 MW fires were slightly overpredicted. This did not significantly affect the passageway results.

Table 2. CBD Tests—Modeling Data

Equivalent Energy Release Rate of Fuel (MW)		1.1	1.1	1.1	1.1	1.1	1.1	2.2	2.2	2.2	2.2	2.2	2.2
Vent Size	(m^2)	0.0	0.4	0.8	1.2	1.6	3.2	0.0	0.4	0.8	1.2	1.6	3.2
	(ft^2)	0.0	4.0	8.0	12.0	16.0	32.0	0.0	4.0	8.0	12.0	16.0	32.0
Average Fire Compartment Temperature	(°C)	592	566	535	445	370	290	671	755	842	827	801	696
	(°F)	1068	1051	995	803	698	554	1240	1391	1548	1521	1474	1285
Average Passageway Temperature	(°C)	251	234	218	185	150	120	464	400	331	302	277	209
	(°F)	454	453	424	365	302	248	867	752	628	576	531	408
Neutral Plane Height	(m)	0.9	1.0	1.1	1.3	1.5	1.8	0.7	0.8	0.8	0.9	1.0	1.3
	(ft)	3.0	3.3	3.6	4.3	4.9	5.9	2.3	2.6	2.6	3.0	3.3	4.3



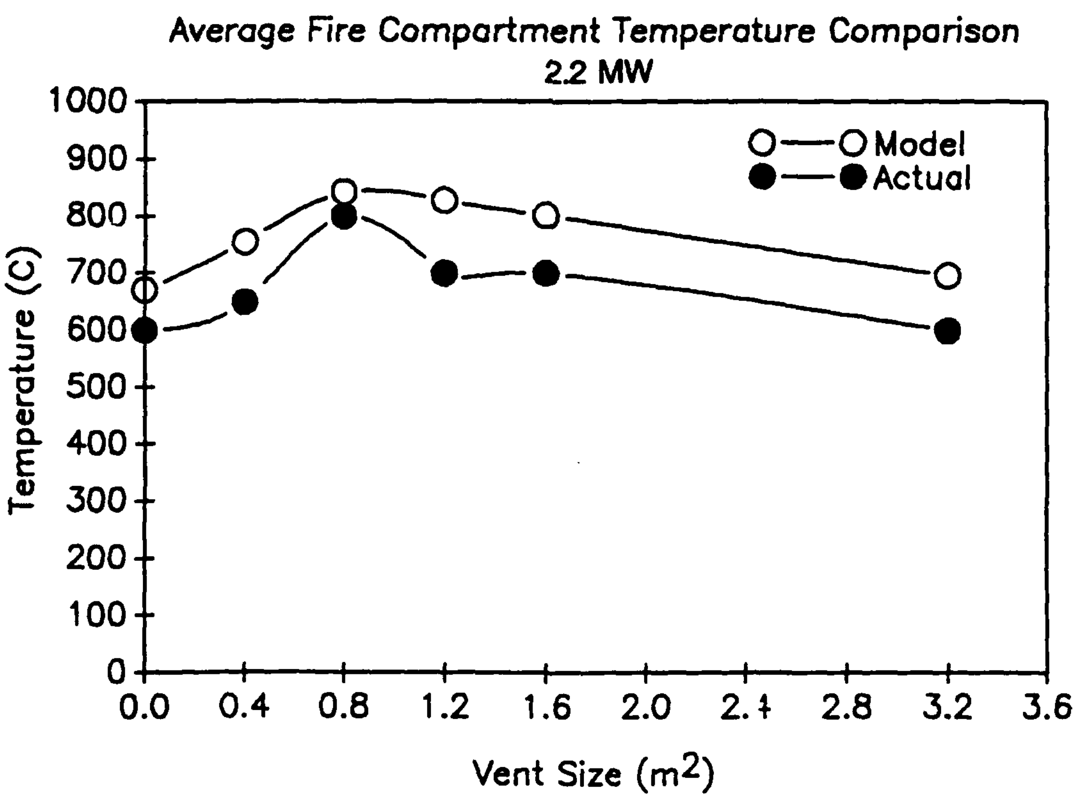
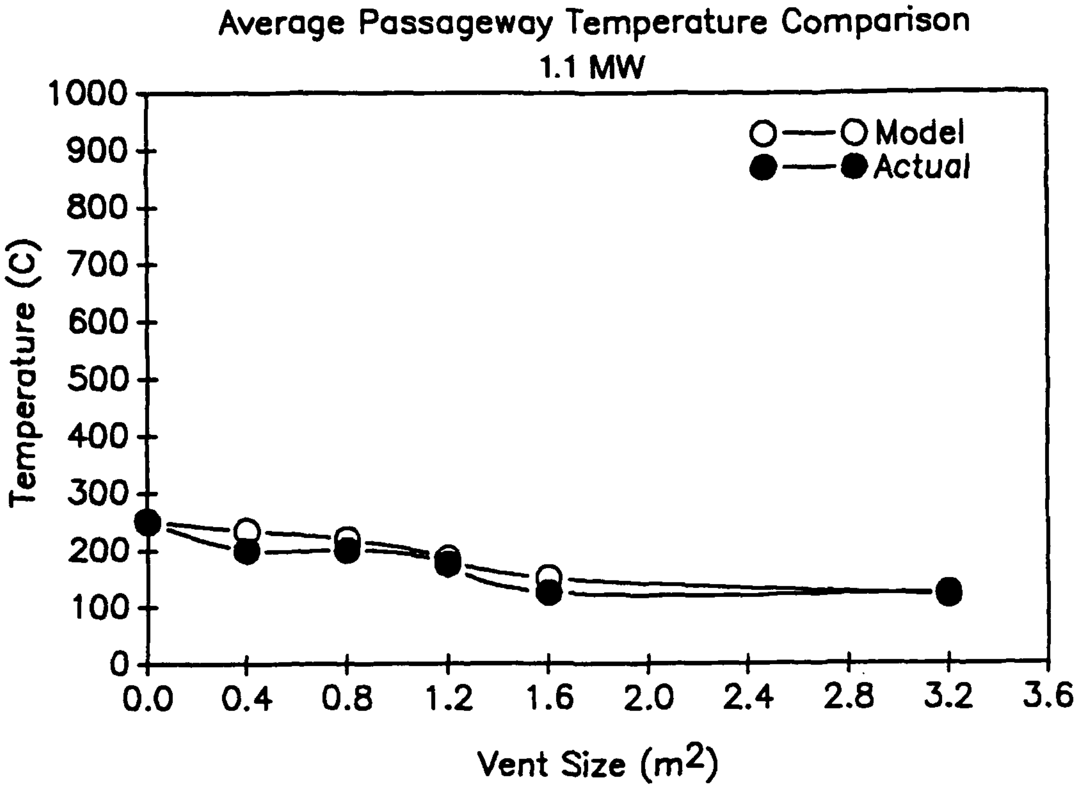


Fig. 10 - Fire compartment temperature comparison



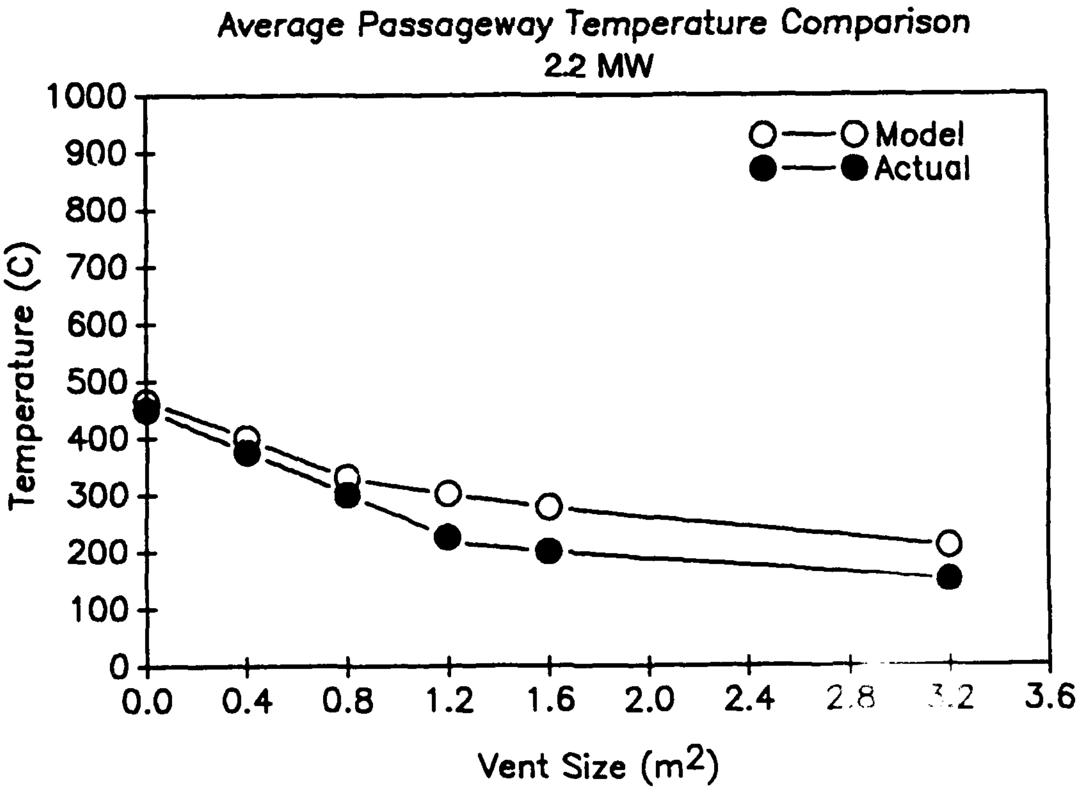


Fig. 11 - Passageway temperature comparison

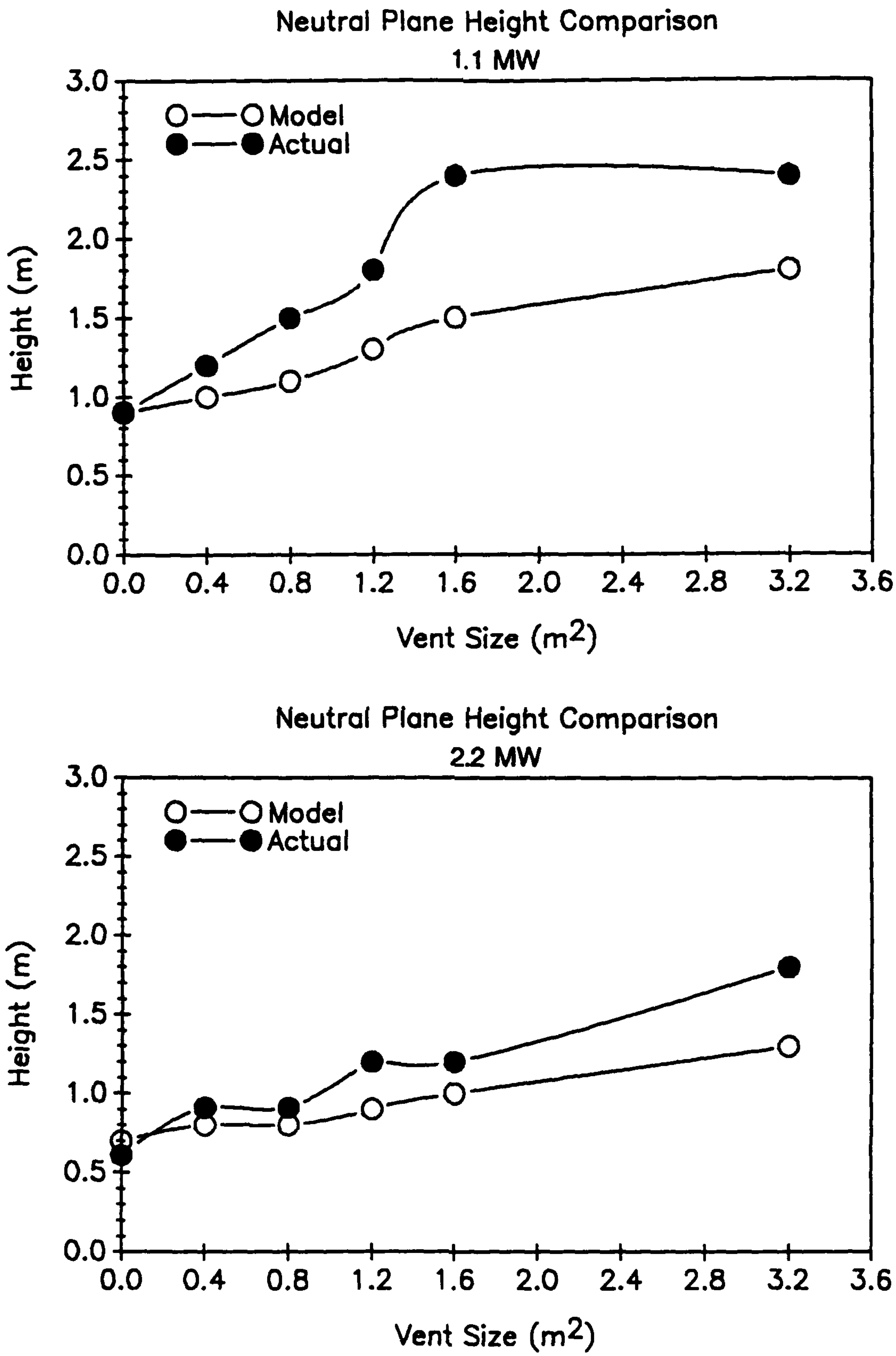


Fig. 12 - Neutral plane height comparison

The comparison of actual and modeled passageway temperatures is shown in Figure 11. The temperature prediction is accurate within 34°C (61°F) for the 1.1 MW fire and within 77°C (134°F) for the 2.2 MW fire. The experimental temperature is the average of the top three thermocouples on the passageway thermocouple tree . It should be noted that the temperatures recorded by these thermocouples varied with height so the comparison may vary by the location of measurement. Overall, the predicted temperatures are a reasonable approximation of the conditions in the passageway.

The comparison of the neutral plane height in the passageway is shown in Figure 12. The predicted heights are somewhat lower than the actual results. The accuracy of the results is also observed to decrease with increased vent size.

Overall, the model was able to predict the conditions both in and around the fire compartment with an acceptable degree of accuracy. The model did, however, lose accuracy for the fuel rich fires and tests containing exceptionally large vents. The modeling, in agreement with the experimental results, suggests that in order to reduce a substantial amount of thermal insult in a major conflagration, the vent size may have to be unacceptably large.

5.0 ex-USS SHADWELL Tests

5.1 Approach

As opposed to removing heat and smoke directly from the fire compartment, the tests on the ex-USS SHADWELL focused on venting adjacent spaces in an attempt to reduce the likelihood of fire spread and allow access for indirect firefighting. This situation might occur where there is a mass conflagration and the compartment of fire origin is considered a "write-off." Fire parties would then attempt to contain and control fire spread in adjacent spaces.

The overall objective of these tests was to determine the reduction in the likelihood of fire spread by venting areas adjacent to the fire compartment. Additionally, fire parties attempting to access an adjacent space might benefit by a reduction in the thermal conditions in areas adjacent to the fire compartment.

The full scale tests were conducted on the ex-USS SHADWELL located in Mobile, Alabama. The Internal Ship Conflagration Control (ISCC) fire test area in the port wing wall of the ex-USS SHADWELL was used for these tests (Fig. 13). The ISCC Fire Dynamics Test Plan describes the basic guidelines for these tests [2]. Baseline burns conducted in the ISCC Fire Dynamics Test Series served to characterize heat/smoke spread in the fire compartment and areas adjacent to the fire compartment [3].

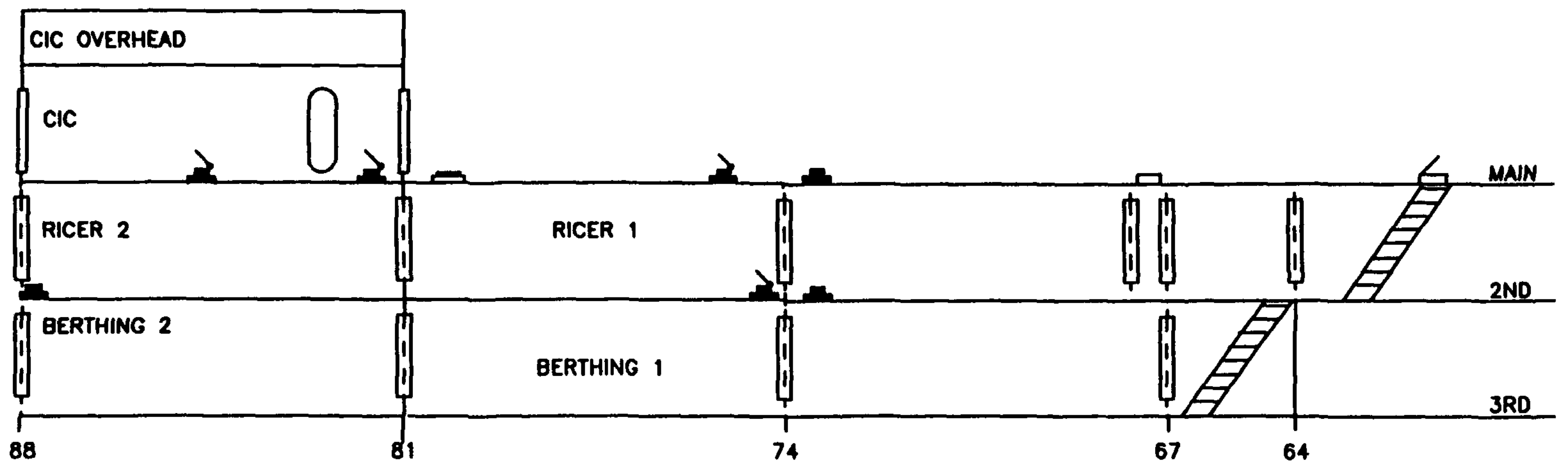


Fig. 13 - ISCC test area setup for natural vent tests (section view)

The compartment above the fire compartment, RICER 2, was vented during these tests. A post-flashover fire was permitted to burn for 20 minutes in each test. At the 20 minute mark, the fuel was shut off and the vents were opened. Three situations were considered: heat build-up and cooling with no venting; heat reduction with natural venting; and heat reduction with mechanical ventilation using a portable blower.

5.2 Setup and Procedure

The principle areas of investigation for the venting test series were Berthing 2, RICER 2, and CIC (Figs. 13 and 14). A post-flashover fire was created in Berthing 2, which heated RICER 2. Venting was performed from CIC.

The post-flashover fire was created in Berthing 2 using a diesel spray fire (Fig. 15). Three steel pans measuring 1.2 x 1.2 m (4 x 4 ft) and 10.2 cm (4 in.) deep were placed on the Berthing 2 deck. Approximately 57 liters (15 gal) of heptane were poured into three pans: 15.1 liters (4 gal) in each of the two outside pans and 26.5 liters (7 gal) in the center pan. These pans were ignited simultaneously and allowed to burn until the pool fires started to die down (approximately 2.5 minutes after ignition). Diesel fuel was then sprayed across the hot pans using three flat fan spray nozzles (Bete Fog Nozzle, Inc. Model FF 073145) positioned over each pan. The hot pans allowed the diesel fuel to combust immediately and eliminated residual fuel build-up in the test compartment. Total diesel fuel flow was nominally 17.4 Lpm (4.6 gpm), split evenly through the three nozzles. Air was supplied naturally to the fire area via vent openings in the hull structure and the two door openings leading to the well deck. The estimated heat release rate of this fire, based on complete combustion, was on the order of 10 MW. Additional details on the test setup are described in Reference [3]. Each fire was allowed to burn for 20 minutes, including the heptane preburn period. At the completion of the fuel system blowdown, the venting scenario was initiated in CIC or RICER 1.

The vent configurations are shown in Fig. 16. One test, Vent_3, did not include a natural vent and established a baseline cooldown of RICER 2 without venting. Three natural ventilation tests were conducted by venting RICER 2 via CIC. In Vent_2, a single 46 cm (18 in.) diameter scuttle (QAS 1-84-2) in the CIC deck was opened. In Ins_13, both this scuttle and a second 53 cm (21 in.) diameter scuttle (QAS 1-81-2) were opened. Both scuttles were installed over raised deck areas 46 cm (18 in.) above the CIC deck (Figs. 17 and 18)). The fact that they were installed in raised deck areas is not believed to have affected the venting data. In Vent_4, the plate covering these two raised deck areas was cut open. A sliding plate mechanism was installed over each raised scuttle area and removed when venting was initiated. Each raised scuttle area was 0.9 x 0.9 m (3 x 3 ft). All three 56 x 168 cm (22 x 66 in.) doors in CIC were open to weather during the venting phase of the tests, but closed during the burn period.

One mechanical ventilation test, Vent_1, was conducted. The water motor fan (RAMFAN 2000 manufactured by RAM Centrifugal Products) was prepositioned in RICER 1. At the end of the 20-minute test, QAWTD 2-81-4 was opened and a smoke curtain

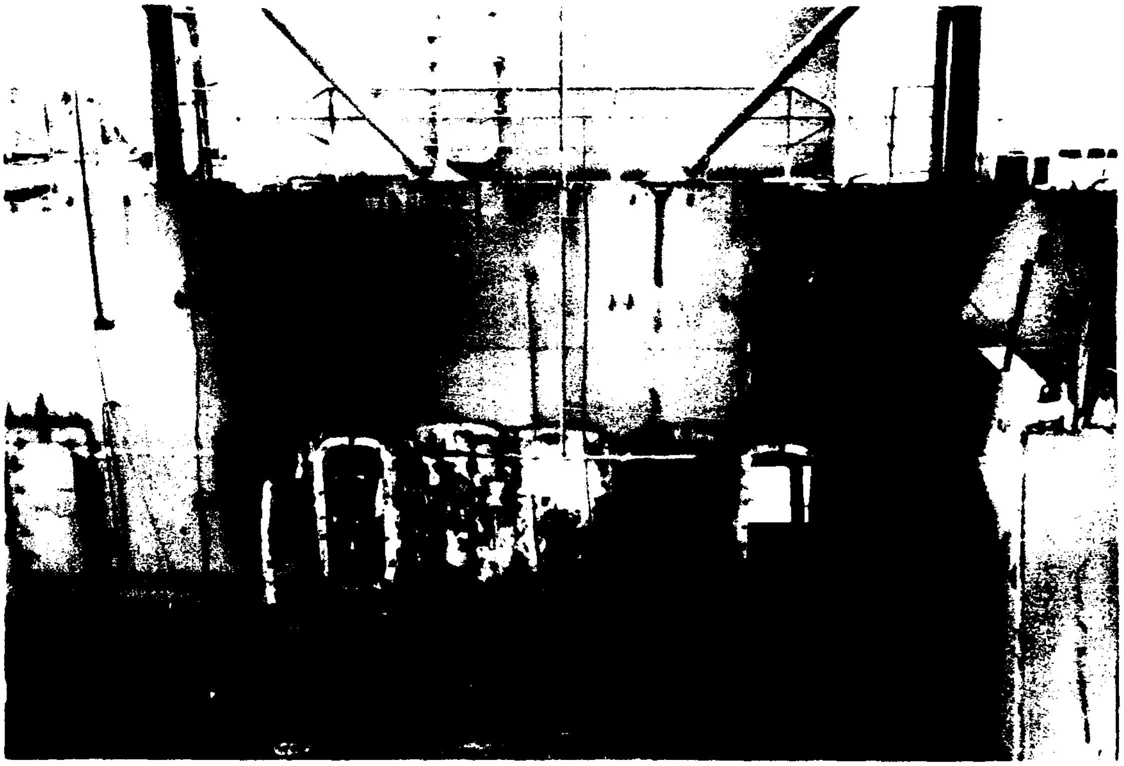


Fig. 14 - Port wing wall of ex-USS SHADWELL showing Berthing 2, RICER 2, and CIC

Fig. 15 - Postflashover fire created in Berthing 2

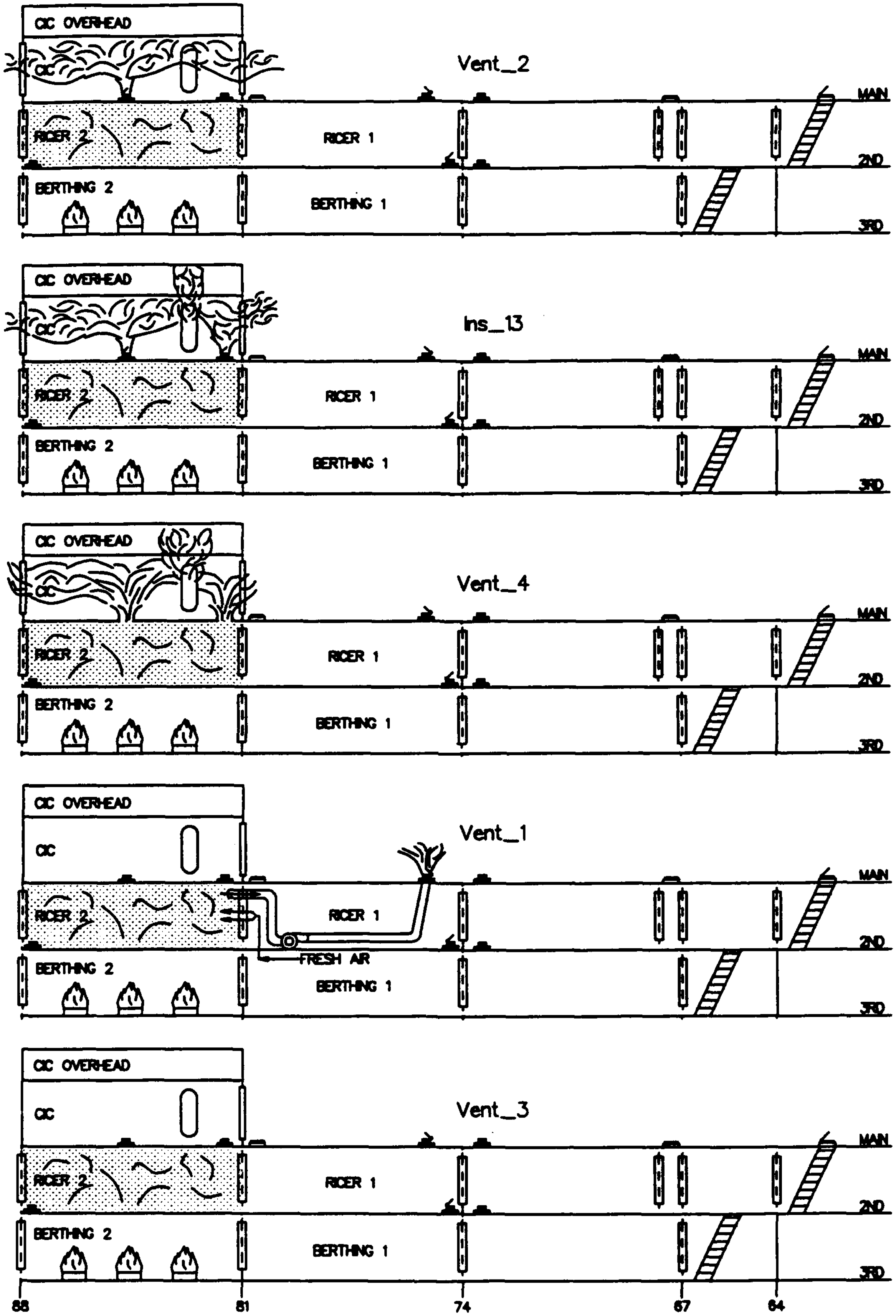


Fig. 16 - Vent configuration for ex-USS SHADWELL tests

Fig. 17 - CIC showing raised scuttles

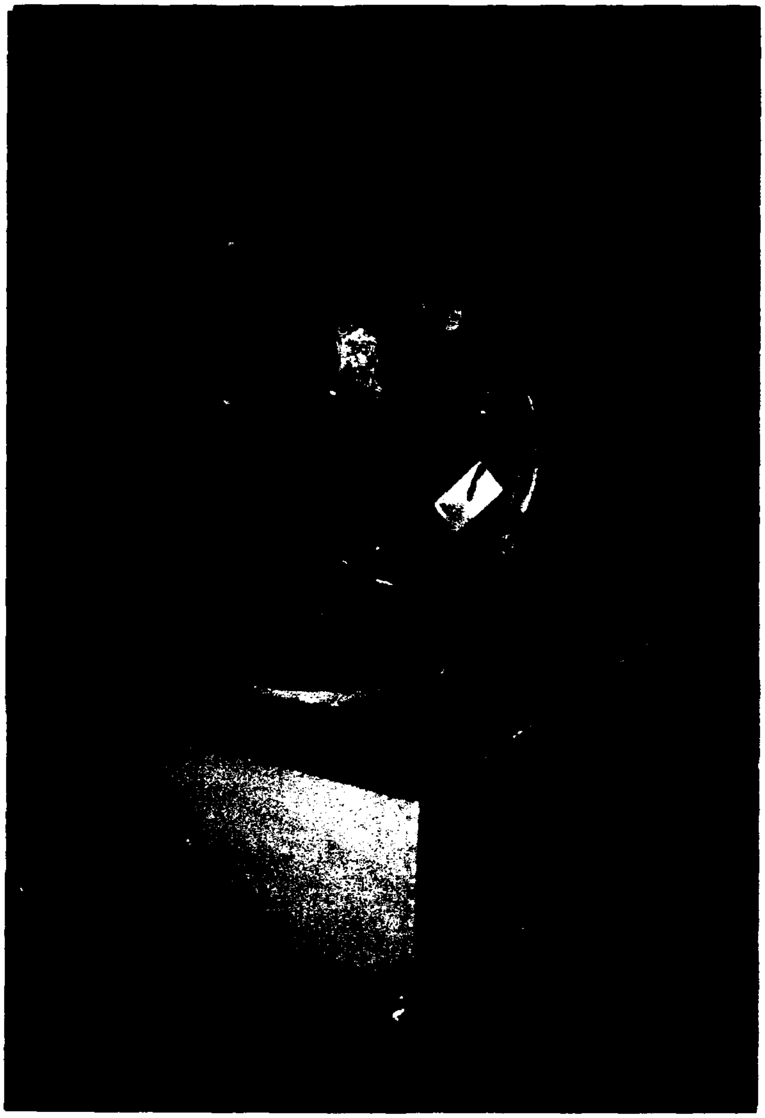


Fig. 18 - Scuttle opened for Vent_2 test

hung to allow resealing of the opening. One 4.6 m (15 ft) long section of 25.4 cm (10 in.) diameter suction ducting was hung with the duct opening positioned just inside RICER 2. A single section of exhaust duct was connected to the discharge side of the water motor fan, which exhausted hot air to weather via QAS 1-76-2 (Fig. 19). Water was supplied to the water motor fan at a rate of 228 ℓpm (60 gpm) from the firemain on the main deck operating at 966 kPa (140 psi). Fresh make-up air was allowed to enter RICER 2 by opening the bottom of the smoke curtain. The bottom one-third (approximately 56 cm (22 in.)) of the curtain was opened. References 4, 6 and 7 provide additional details on the capacity of the RAMFAN and the fresh make-up air technique.

Standard instrumentation for the ISCC test area is described in References 2 and 3. For these tests, the temperature data in RICER 2 are the pertinent measure of venting effectiveness. Two strings with thermocouples were located 61, 91, 120, 152, and 183 cm (18, 36, 54, 72, and 90 in.) above the deck measuring the RICER 2 air temperature (Fig. 20).

5.3 Results

Figures 21 through 25 and Table 3 summarize the results of the ex-USS SHADWELL tests. These data show that the temperatures in RICER 2 were relatively unaffected by natural ventilation until the test with the largest vent area was conducted (Vent_4). This is illustrated by the times required to cool the compartment from 300°C (572°F) to 200°C (392°F). The average of the two thermocouple strings at the conclusion of the fire was on the order of 300°C (572°F). The time required to cool the compartment was unaffected by the presence of a 0.2 m^2 (1.8 ft^2) vent area and a 0.3 m^2 (4.2 ft^2) vent area as shown in test Vent_2 and Ins_3, respectively (Figs. 21-23). The recovery times (times to cool the compartment) were unaffected until test Vent_4 where the vent area was 1.7 m^2 (18 ft^2) (Fig. 24). The slightly longer recovery times for the two small vent tests (Vent_2 and Ins_13) vs. the natural test (Vent_3) may be due to effects from ambient wind conditions (see Table 3). In Vent_4, the time required to cool the compartment decreased from approximately 22 minutes for no vent opening to 17 minutes for the larger vent opening.

The modest cooling rates recorded during the natural vent tests were, to a certain extent, a product of the scenario. Under normal fire conditions, natural vent flow is driven by three forces:

1. buoyancy produced by the differences between gas (smoke) and ambient temperatures,

2. buoyancy created by the fire, and

3. effects of external winds and air movements with respect to vents and cracks which permit leakage.

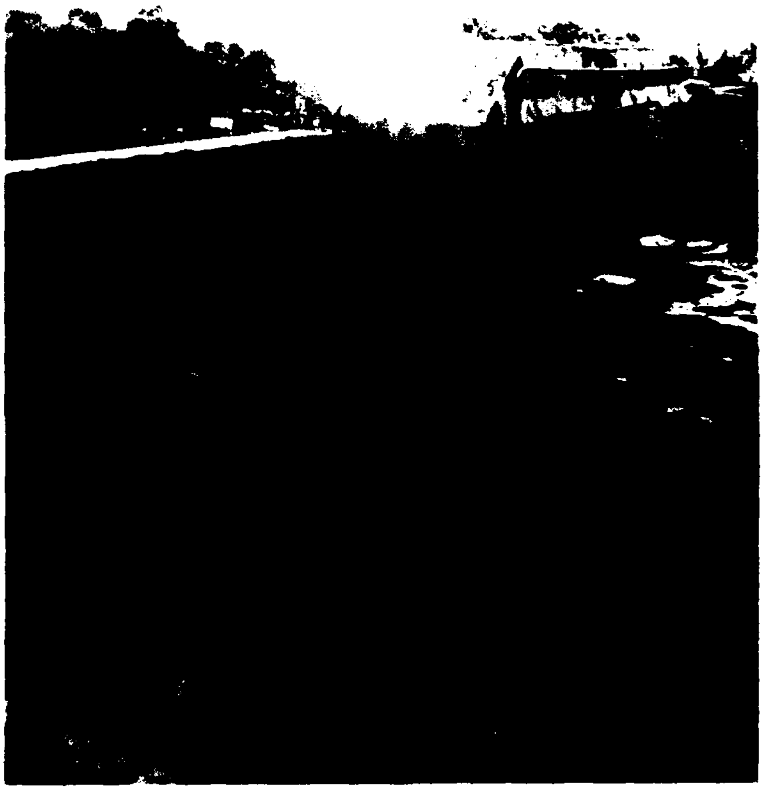


Fig. 19 - Water motor fan discharge duct in Vent_1 test

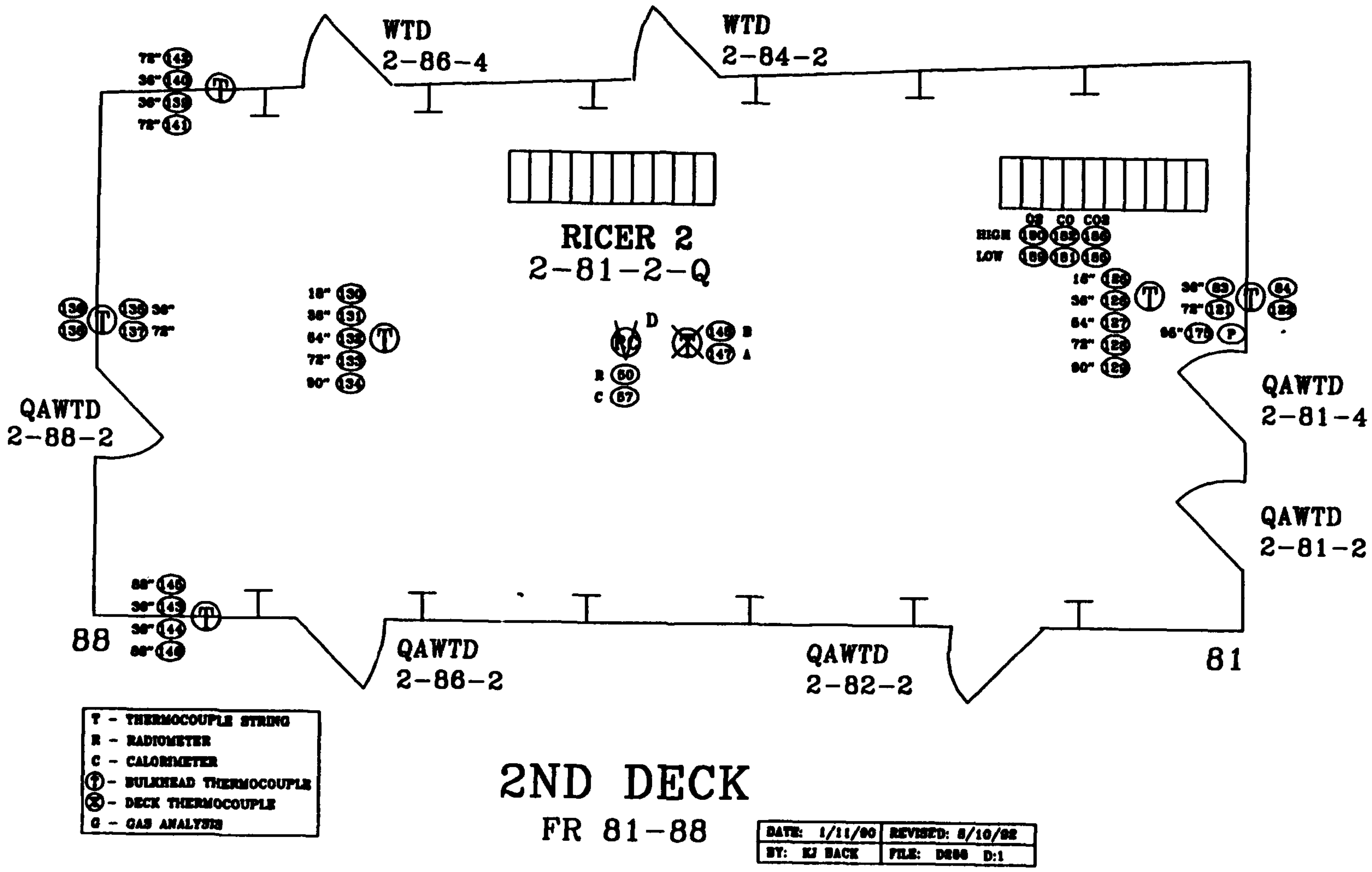


Fig. 20 - Instrumentation plan view of RICER 2

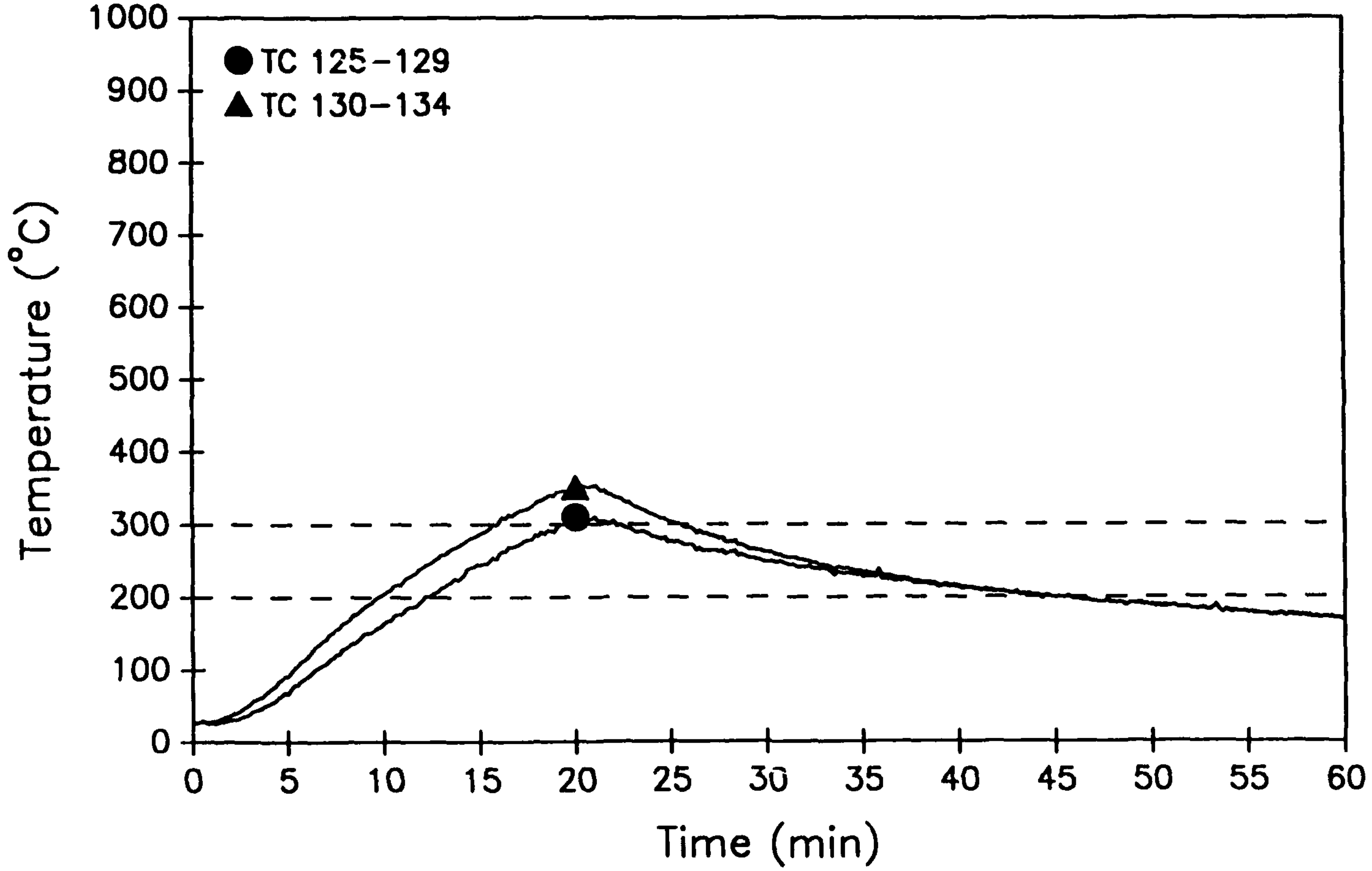


Fig. 21 - Average of RICER 2 air temperatures for Vent_3, no venting

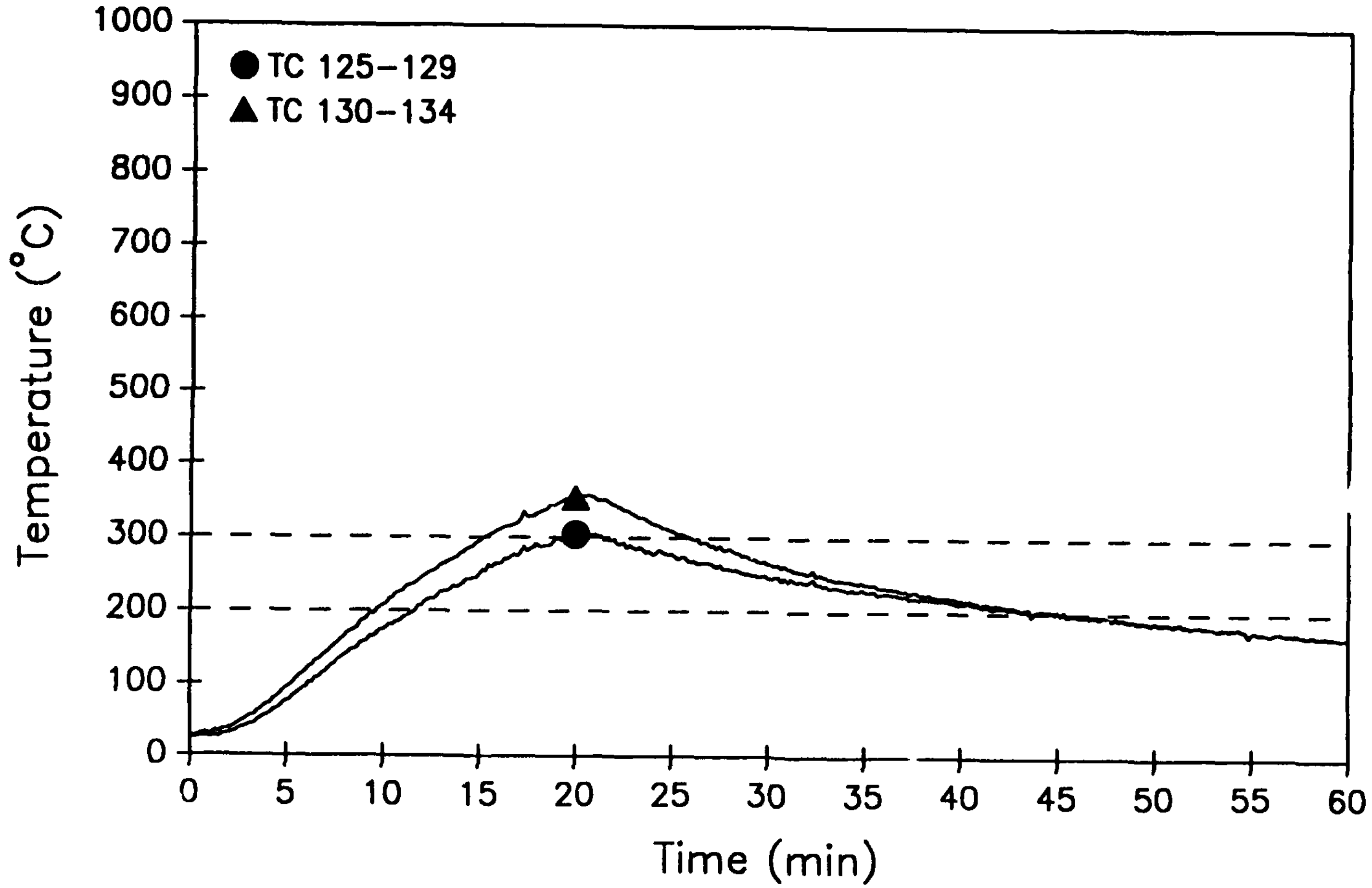


Fig. 22 - Average of RICER 2 air temperatures for Vent_2, one scuttle open

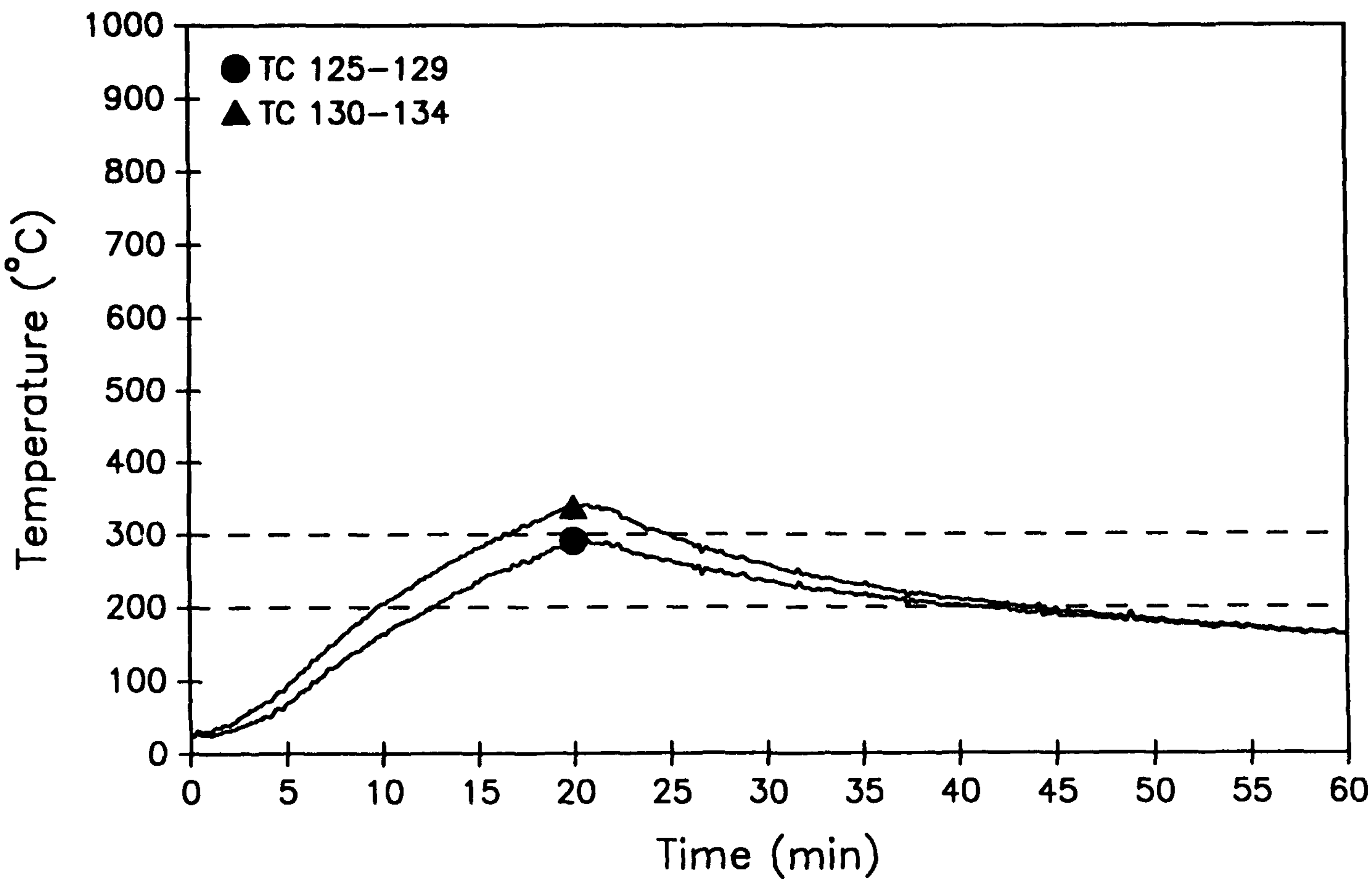


Fig. 23 - Average of RICER 2 air temperatures for Ins_13, two scuttles open

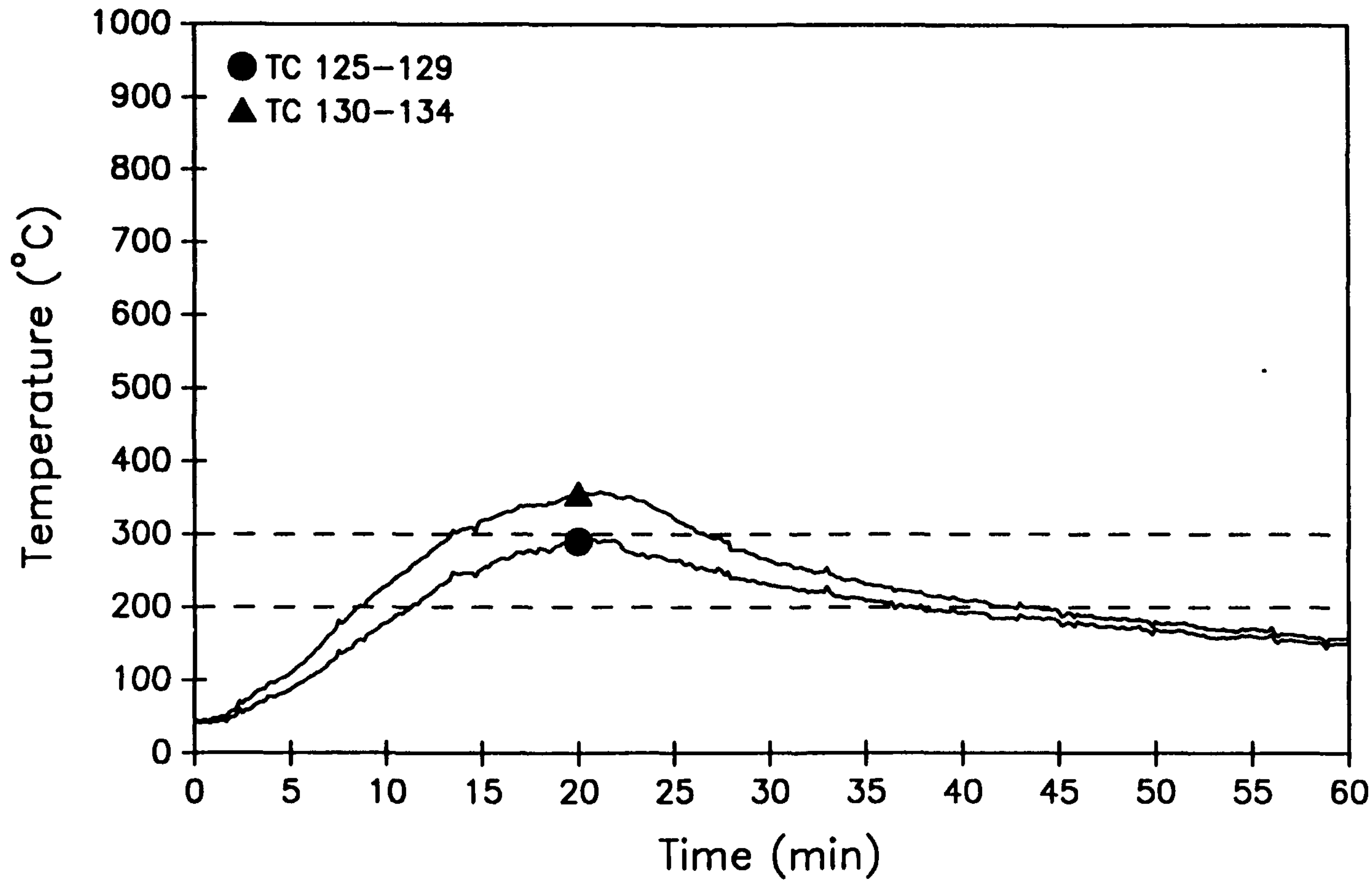


Fig. 24 - Average of RICER 2 air temperatures for Vent_4, raised hatch vent openings

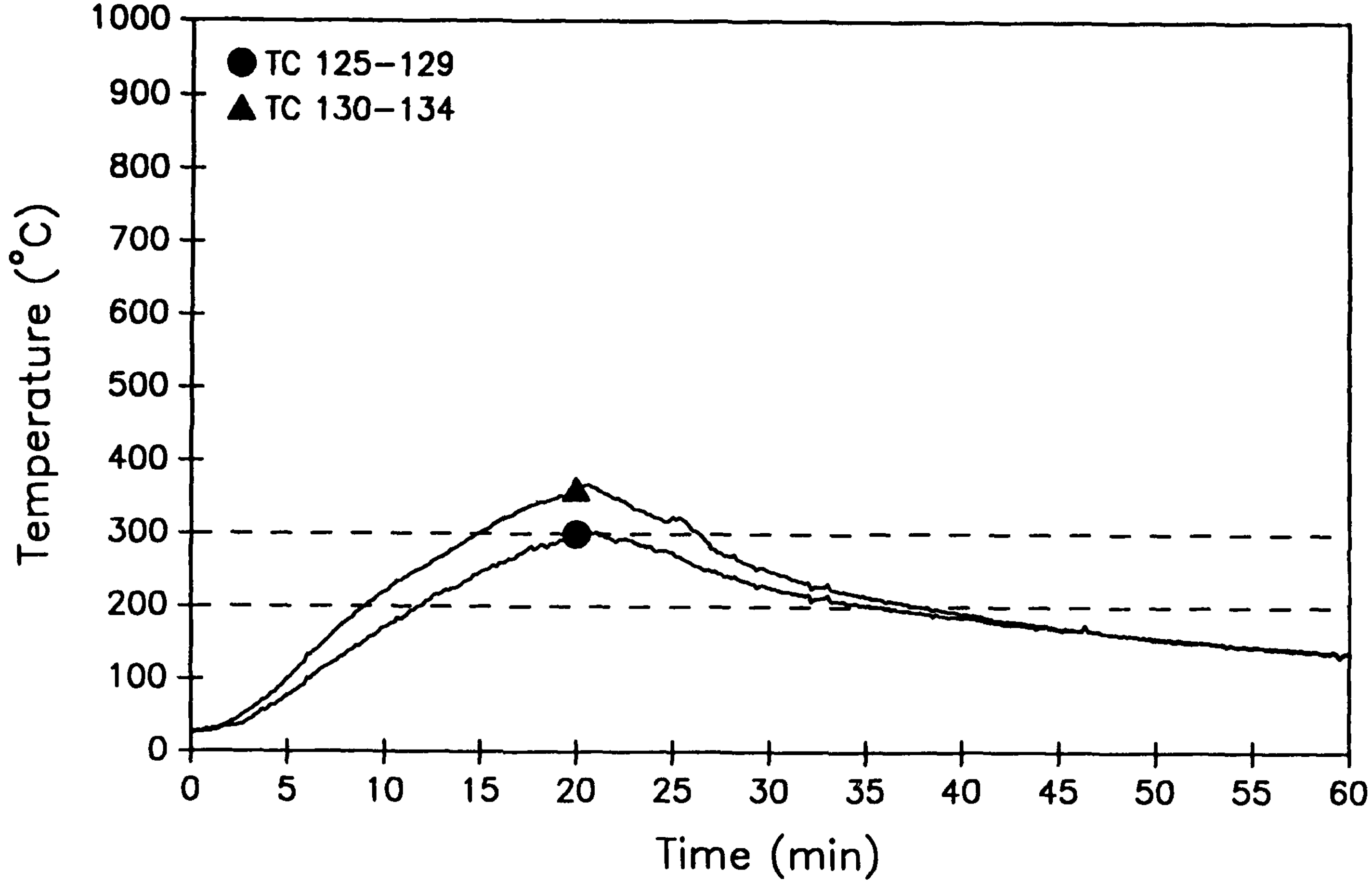


Fig. 25 - Average of RICER 2 air temperatures for Vent_1, water motor fan ventilation

Table 3. SHADWELL Ventilation Test Summary

Test No.	Ventilation	Vent Area m^2	(ft^2)	Time from 300 to 200°C (minutes)	Ambient Wind Condition (speed/direction)
Vent_3	No	--	--	22	High/North
Vent_2	Natural Overhead	0.2	(1.8)	24	Low/North
Ins_13	Natural Overhead	0.4	(4.3)	24	Low/North
Vent_4	Natural Overhead	1.7	(18.0)	17	Low/North
Vent_1	Forced	Water motor fan		13	Low/South

In this scenario, the forces produced by the difference in gas temperatures drive the flow through the natural vent openings. Initially, the flow is induced by a buildup in pressure due to thermal expansion of the gases in the compartment. RICER 2 was originally airtight, but cracks and warpage have resulted due to multiple fire insults. Once any pressure is released via cracks in openings, the flow is dependent on the temperature difference between the heated gases and ambient conditions and ambient wind moving across the vents. The heated gases have a lower density causing them to rise. Figures 26 and 27, profiles of the temperatures in RICER 2, show that there is virtually no temperature gradient in the compartment. Figure 28 shows representative temperatures in CIC for Vent_3, which are higher than the ambient air. These temperature profiles show that there is only a modest temperature gradient.

As the gases rise out of the compartment through the vent, cooler air is drawn in to replace the exiting gases. In the top vent scenario, the entering gases must share the same vent opening as the exiting gases. Small-scale testing has indicated that flow through a top vent may be bi-directional [8]. This sharing of the same opening effectively reduces the vent efficiency. If two vents were installed, one high to release the hot gases, and one low to allow cooler air to enter, the vents may have been more effective.

During the water motor fan test (Vent_1), the compartment was observed to cool twice as fast as in the small vent tests (Vent_2 and Ins_13). The time required to cool the compartment was observed to drop from 22 minutes for an unventilated compartment to 13 minutes for forced ventilation. During this test, the hot gases were removed high in the doorway of QAWTD 2-81-4 while new air was allowed to enter low (bottom 0.56 m (22 in.)) at the same location. This configuration reduces the problems observed during the natural ventilation tests where the effective vent area is reduced because of fresh air intake. If the cooler air was allowed to enter the compartment from the side opposite the exhaust, the vent efficiency of the water motor fan may have been increased. The extent of the heat vented in Vent_1 is characterized by the resulting damage to the vent ducting (Fig. 29).

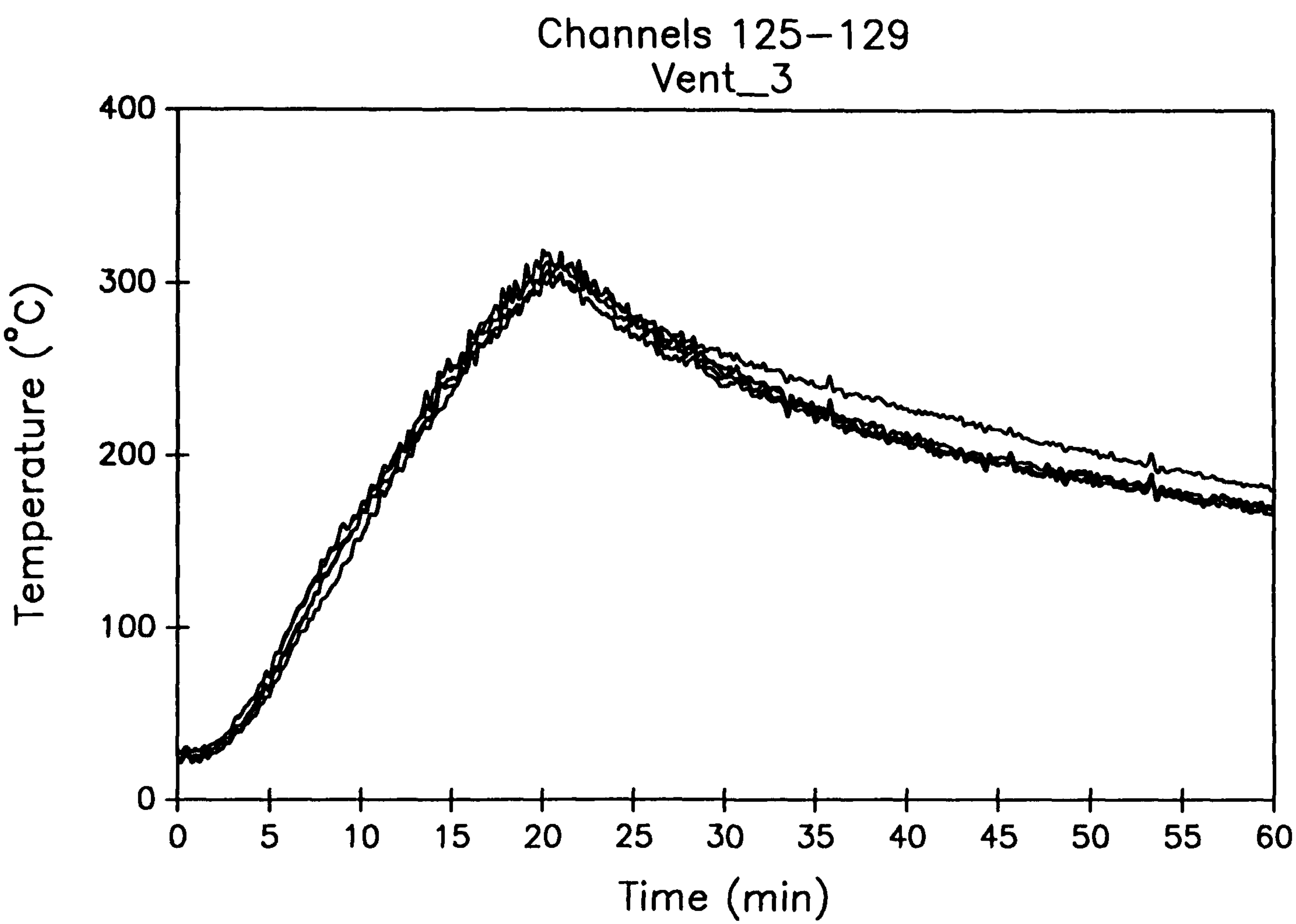


Fig. 26 - Air temperatures in RICER 2 Forward for Vent_3
(See Fig. 20 for thermocouple locations)

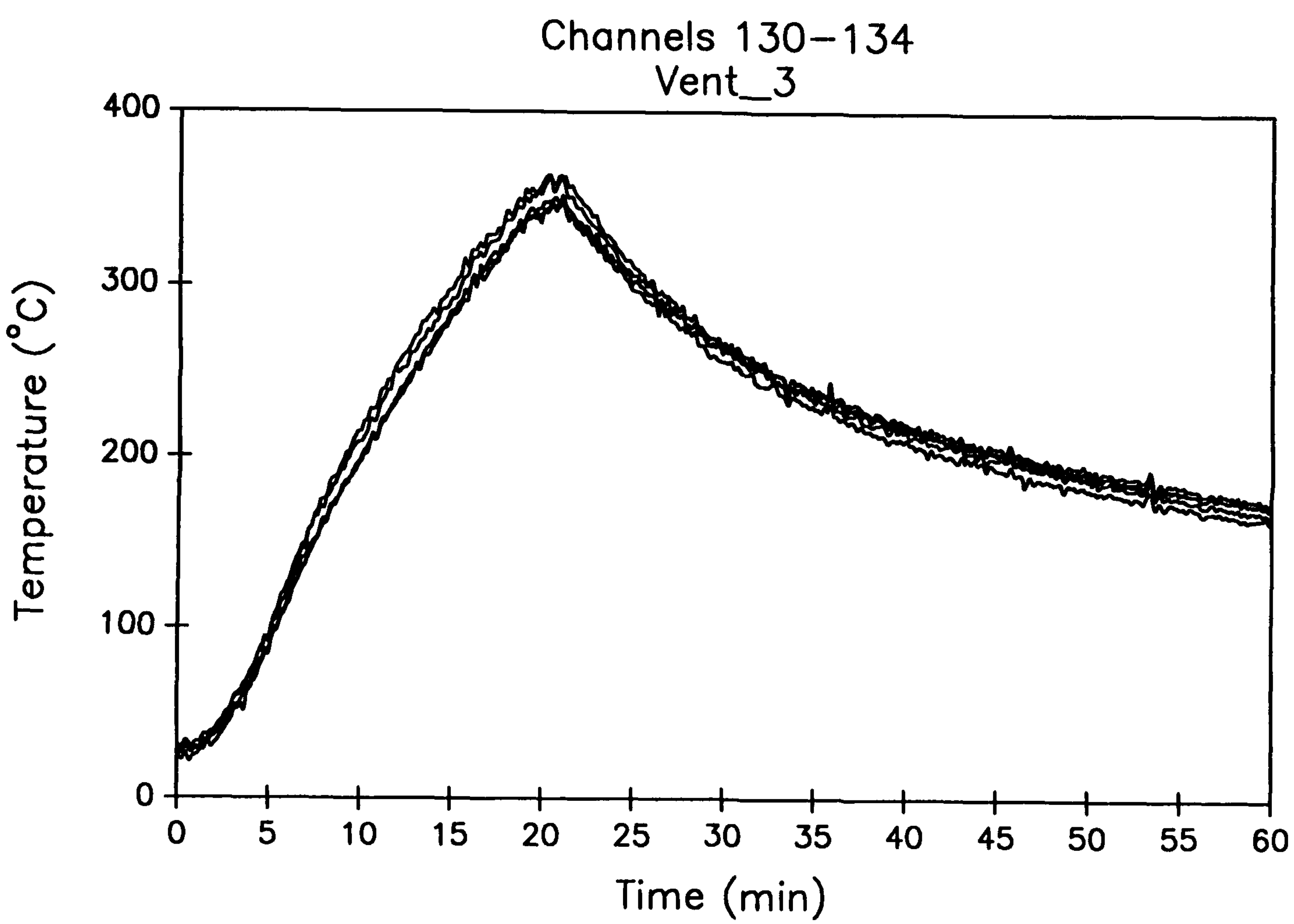


Fig. 27 - Air temperatures in RICER 2 Aft for Vent_3
(See Fig. 20 for thermocouple locations)

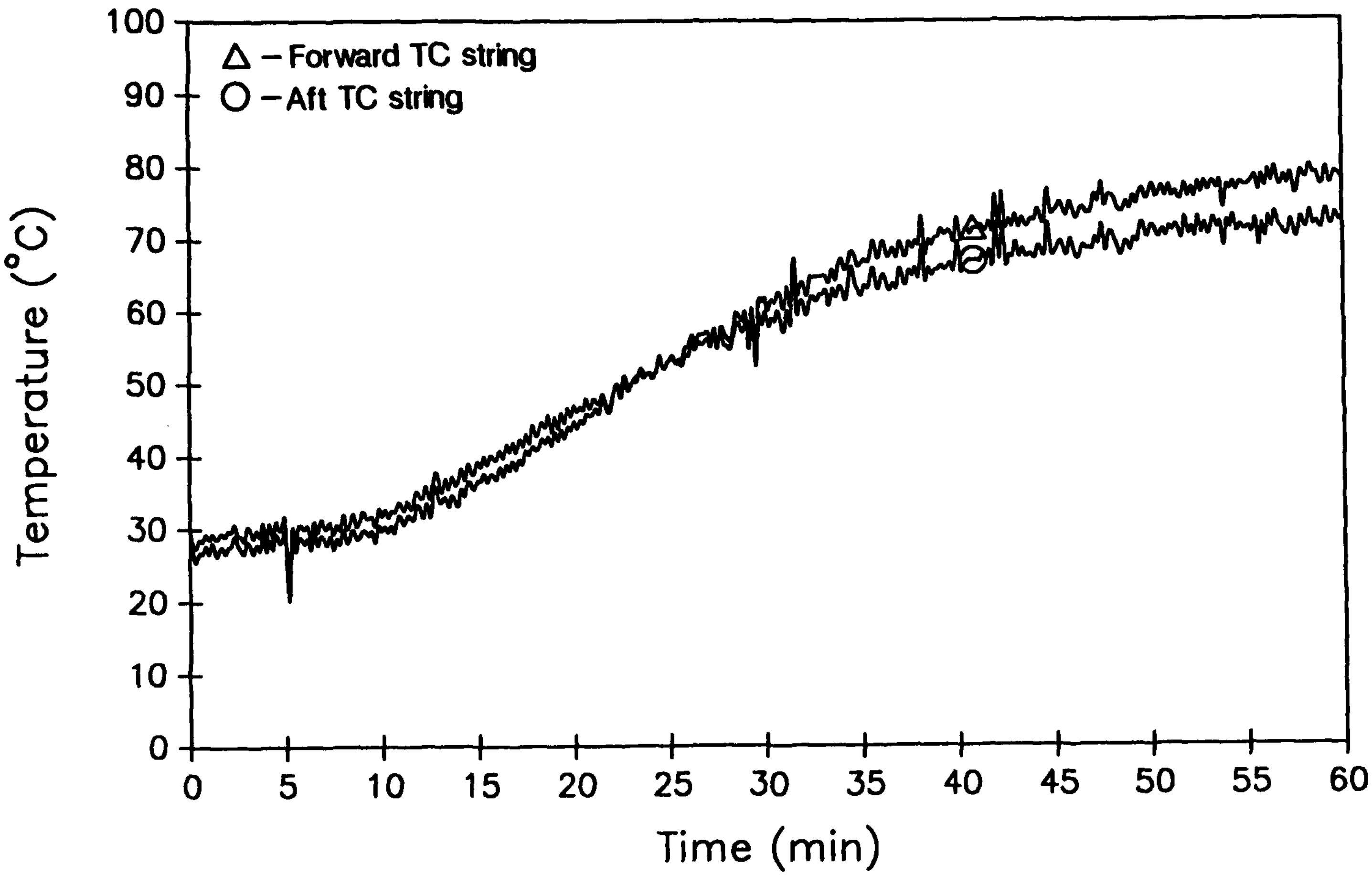


Fig. 28 - Average air temperatures in CIC for Vent_3

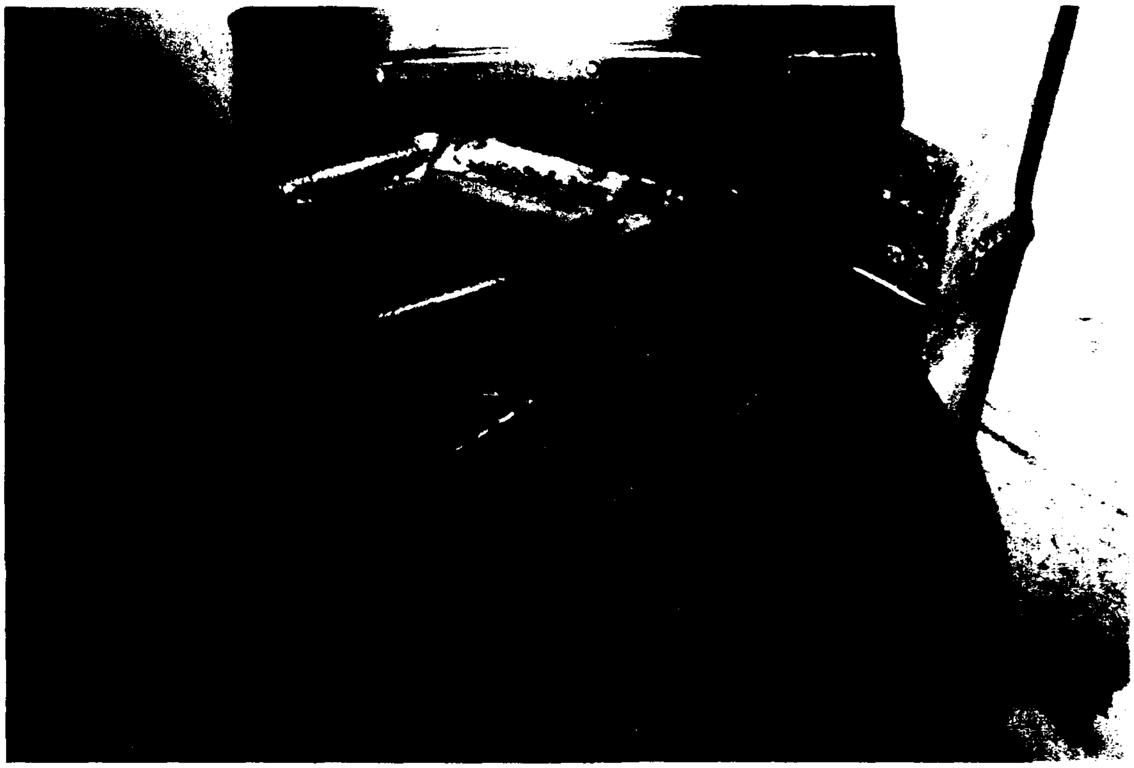


Fig. 29 - Damage to water motor fan duct due to heat
in Vent _1 test

5.4 Modeling

An attempt at modeling the full scale tests was made using FAST. A total of ten iterations were made, of which only two ran to completion. Apparently the size and construction of the ship combined with the ventilation conditions (or lack of) caused problems in the heat transfer algorithms. The two runs which ran to completion resulted in overprediction of temperatures in RICER 2 and slower cooling rates than occurred during the actual tests. While this model has a top (vertical) vent algorithm, it requires an input heat release rate and inherently assumes an actual burning fire. This is not the situation here, where there is "hot plate" heating of the compartment. A model which assumes a well-stirred situation rather than a two-zone condition might be a better approximation of this situation. This aspect will be investigated in modeling being conducted with the fire dynamics analysis [3].

6.0 SUMMARY AND CONCLUSIONS

An analysis on the effects of venting both the fire compartment and adjacent compartments was conducted. The primary objective of this analysis was to quantify the reduction of the thermal insult to reduce and/or eliminate the likelihood of fire spread and improve firefighting access.

These tests focussed principally on the relief of the thermal insult resulting from a large fire. Consequently, the *amount of natural vent area required to significantly reduce* heat is large, particularly where the difference between ambient and the space temperatures is relatively low (e.g., adjacent space vs. fire compartment). The magnitude of vent sizes required to reduce heat was shown in these tests.

The results of the tests might lead one to believe that it may be fruitless to cut a vent of 0.09 m^2 (1 ft^2) as currently recommended in NSTM 555. This is not the case. **The CBD data clearly show that even small vents are effective in relieving smoke. In many cases, this may be as or more important than relieving heat.** Relieving smoke should improve visibility for better access and identification of the exact location of the fire. This may be a more important factor for pre-flashover fires, where the exact location of the fire is difficult to identify. A potential liability in venting pre-flashover fires is the increased air available for burning. In the post-flashover situation, this is not of particular concern. In the pre-flashover situation, judgement must be made. This is particularly true for under-ventilated fires where additional air from an opening in a bulkhead may result in increased burning. For example, it was observed that crumpled paper on the deck of CIC charred as a result of heat from RICER 2. When the paper was taken out to weather, it had a tendency to ignite. The effects of a vent in the overhead only on the fire burning rate are less well established. There are data that suggest that burning rates with this top venting only are considerably less than burning rates in compartments with similar vents in bulkheads [8,9].

The traditional tactic of closing off all air to a fire zone limits potential air for burning but may increase access time if the zone becomes smoke and heat logged. If a fire can be contained in its initial stages by shutting off the air supply, then certainly this tactic is appropriate. Where ventilation of a fire cannot be secured, e.g., through a battle-induced opening to weather, then the introduction of additional vents in the firefighting attack may be appropriate. The option to vent during such a fire, given that sufficient personnel resources are at hand to mount an attack, should be considered.

The need to provide fresh make-up air when venting has been demonstrated in these tests and other tests conducted in the port wing wall of the ex-USS SHADWELL [6,10]. The use of the water motor fan for venting, in combination with natural or mechanically induced fresh air make-up, has been shown to be a highly effective tactic for gaining access and mounting an indirect firefighting effort. Specific tactics where smoke curtains are used and fresh air is throttled in naturally or supplied mechanically in a positive pressure mode have been demonstrated. These tactics should be more widely described in the technical manuals. They should be adopted in training curricula, training school scenarios, and Fleet on-board training drills, recognizing that both the positive and negative effects should be understood within the context of a given situation.

Specific conclusions with respect to compartment venting are the following:

6.1 Fire Compartment Venting

a. Venting the fire compartment reduces the thermal and smoke insult to adjacent spaces but in the case of a fuel rich fire may increase the temperature of the fire compartment itself.

b. Any size vent has some effect on reducing the threat to the areas around fire compartment. However, in order to significantly reduce the thermal threat during a major conflagration, dramatically larger vent areas are required compared to that suggested in NSTM 555.

c. Small vents can be effective in venting smoke.

d. The conditions in and around the fire compartment were accurately modeled using the fire model FAST.

6.2 Adjacent Compartment Venting

a. Since there is little natural buoyancy (e.g. from the fire), naturally venting hot air in an adjacent space is not particularly efficient. The heat in the adjacent compartments results from the stored energy in the steel. Large vents are required before any noticeable improvement in cooling is noticed.

b. Mechanical venting using a portable blower was very effective in cooling an adjacent compartment, compared to natural venting.

c. To improve venting efficiency in an adjacent compartment, a make-up air flow path to supply fresh air is required.

d. The utility of currently available fire models to address bulk heating and venting of compartments adjacent to a fire compartment is limited.

7.0 RECOMMENDATIONS

Based on the results of this study, the following recommendations are made:

a. The recommendation in NSTM 555 for a 0.09 m^2 (1 ft^2) minimum size for a vent should be retained, along with the emphasis that larger vents will be more effective. Round holes should be cut to relieve structural stress as recommended by NAVSEA engineers.

b. Venting tactics in NSTM 555 and other pertinent technical manuals should be updated to
   (1) stress the importance of fresh make-up air supply when venting;
   (2) stress the importance of venting in the relief of smoke, so that access may be easier; and
   (3) describe the option of venting during a fire (even a pre-flashover fire), with appropriate cautions for the implications to adding air to the fire.

   Specific tactics described in References 6 and 10 should be integrated into the technical manuals.

c. Along with the integration of improved venting information in the technical manuals, training curricula, training school scenarios, and Fleet on-board training drills should be modified to include improved venting tactics.

d. Efforts to improve fire modeling, particularly for heated adjacent compartments, should be continued.

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